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STRUCTURAL PRINCIPLES CONTROLLING THE OCCURRENCE OF ORE IN THE KOLAR GOLD FIELD.

W. JAMES BICHAN.

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ABSTRACT.

The Champion lode of the Kolar gold field is a persistent quartz-filled fracture system extending north and south in a similarly oriented basin of infolded hornblende schists and allied rocks. It is the clearest example known to man of the influence of structural control in the formation of bodies of gold-bearing ore.

The relict of highly altered eruptives presently represented by the schist series is surrounded and underlain by a complex of granitic rocks. The igneous activity, as evidenced by certain of the invasive members of the plutonic suite, has also been responsible for the economic mineralization of the lodes, and for pegmatites both earlier and later than the gold-quartz veins.

The occurrence of economic widths of quartz, to which the gold values are confined, is subject to a clearly portrayed structural control. Drag

openings, and lengths of vein fissure opened up in response to pressures acting upon thrust-isolated hanging-wall wedge blocks in such a way as to move them away from the foot-wall locally, have provided the host chambers for ore.

The mineralization is relatively simple: sulphides, including pyrite, pyrrhotite, galena, and chalcopyrite, compose less than one per cent of the ore. The only gangue minerals present in any abundance are pale green pyroxene and the micas, derived from the wall-rock constituents partly by reaction. Tourmaline, albite, quartz, and carbonate have been derived from the solutions that deposited the gold.

The rocks of the region and the gold deposits are all of pre-Cambrian age. Their character, and persistence as workable shoots to great depth, renders these veins akin to deposits of similar age found in Australia, Canada, and other parts of the world.

Development of the mines has been straightforward and detailed geological direction considered unessential. The latter policy had resulted in the by-passing of vast tonnages of ore in the upper level horizons throughout the first fifty years of operations in the field. In later years attention has been equally divided between attempts to locate these valuable remnants and the prosecution of exploration to great depth.

This paper submits a number of relatively new patterns for further study:

(1) the reasonable indication, from the underground workings of the field, that the schists represent the expression of a synclinal structure possessing a complexity of folding not hitherto realized.

(2) the later pegmatite intrusions spatially associated with the gold-bearing quartz are co-magmatic emanations and not far removed in age.

(3) through a combination of initial separation and late redistribution processes the gold has to some extent become concentrated along both the anticlinal and synclinal portions of fold structures exhibited by the veins.

(4) the folds are due to structural deformation of the vein fissures during or prior to the consolidation of most of the quartz.

(5) the localization of quartz masses is interrelated with the structural deformation responsible for the presence of the folds.

(6) the localization of the gold is an outcome of the same deformation processes that brought about the ultimate disposition of the quartz.

(7) the correlation of all available geological evidence would be productive of considerable economies in the development of the ore bodies of the Kolar field.

(8) the use of the diamond drill in an intelligent manner in selected locations would contribute to the more efficient development of the mines.

(9) there is now sufficient evidence in sight from the underground exposures to show conclusively *why ore is where it is*, and to enable the skilled technician to make a useful estimate of the barren sections of the lodes.

(10) persistence of economic pre-Cambrian gold deposition to the ultimate physical depths of mining is proven in this locality.

INTRODUCTION.

THIS paper is founded upon eighteen months field work completed in 1938 during the author's period of service as geologist with The Mysore Gold Mining Company Limited. Subsequent development of the ideas expressed has benefited greatly through a year spent in post-graduate study at Harvard

University, where the greater proportion of the laboratory study of thin and polished sections was carried out.

Other geologists with whom it was possible to arrange discussions of certain general problems have stimulated the author's views with regard to the more theoretical points treated. Whatever merit attaches to this presentation must be attributed to their encouragement and influence, while at the same time the obvious defects are solely the burden of the author.

Among those to whom especial thanks are due should be mentioned: Ellsworth Y. Dougherty, Frank Ebbutt, L. C. Graton, B. J. Keating, Donald H. McLaughlin and H. A. Martin.

The examples figured in the text are drawn from the Mysore mine property through the facilities of John Taylor and Sons Limited; they might equally have come from any one of the four mines operating on the Champion lode system. As a result of brief visits to all of the mines it can confidently be stated that the basic principles established for the Mysore property are applicable throughout the present extent of the productive portion of the Kolar field.

The Mysore mine was the most favourable for initial study, both on account of its premier economic importance in having produced about one-third of the gold from the entire field, and nearly one-half of the total dividends, and from the fact that its older workings were more readily accessible than in the other mines.

GENERAL GEOLOGIC BACKGROUND.

Narrow elongated belts of pre-Cambrian metamorphic rocks exist as scattered remnants throughout the gold-bearing region of southern India. None of these is more than a half-a-dozen miles in width, but the length from north to south may be twenty to thirty times the narrower dimension and thus extending for some tens of miles in individual cases.

The schists all belong to what has been called the lower division of the Dharwar System. It comprises essentially hornblende schists and amphibolites that have probably been derived through the regional metamorphism of basic igneous eruptives. The upper division of the same system is composed of chlorite schists and does not outcrop in the near vicinity of the Kolar field.

Interbedded with the subsequently metamorphosed flows were ferruginous sandstones. This formation may be observed to outcrop steeply as a narrow ridge of resistant quartzite two miles to the west of the surface expression of the lodes. A corresponding outcrop is said to appear a similar distance east of the vein system, but as the quartzites lie at an angle not greater than forty-five degrees in the latter locality they are not such a conspicuous feature as they are to the west. These rocks correspond to the "iron formation" of the Lake Superior region of North America, and of numerous occurrences throughout the Canadian shield area.

According to Smeeth (19) [1] and others, the Dharwars have been intruded by certain acid rock types, designated the Champion gneiss, which occur in

[1] Numbers in parentheses refer to Bibliography at end of paper.

intimate association with them and exhibit a similar high degree of metamorphism. This comparatively fine-grained micaceous granite gneiss outcrops to the east of the Kolar mines as a band paralleling the general direction of the schist belt and the strike of the lodes, and of a width varying between three and five thousand feet.

Smeeth's description (19) of the gneiss suggests that it

> . . . is usually highly crushed and frequently contains conglomerate composed not only of round to sub-angular fragments of the various granitic materials but also patches and lumps of the adjacent Dharwar rocks including the banded ferruginous quartzites.

The two closely associated metamorphic types are surrounded and underlain by a widespread igneous complex termed the Peninsular gneiss, from the fact that it constitutes practically the whole of southern India. The contact of the adjacent member of this intrusive complex with the Dharwar system and its associated rocks exhibits a gradual transition. Highly altered schists and gneisses untouched by the intrusive grade through a hybrid granite containing inclusions of the invaded rocks, and pass to an igneous type that is comparatively uncontaminated. Smeeth (19) is well supported by the field evidence in his conclusions:

> Evidence of the intrusion of the Peninsular gneiss into the Dharwar schists is abundant and the former bristles, to a variable extent, with lenses, patches, and fragments of the Dharwars chiefly, as might be expected, belonging to the lower or hornblendic division.

An earlier period of invasion within the scope of the Peninsular complex appears to be that responsible for the Champion gneiss, and a micro-pegmatite gneiss (dogger) that is likely to have been originally a pegmatite. The present Peninsular gneiss-schist contact owes its existence to a second period of igneous activity, to which the Champion lode may also be credited. The final outbursts of igneous action produced a definite granitic type, comparatively unaffected by pressure, and that outcrops conspicuously as rounded hills of almost bare rock rising several hundred feet above the general level of the surrounding plain. To this phase may be attributed the younger pegmatites encountered underground.

The latest crystalline consolidation has been called the Closepet granite and is well developed as a band extending through the State of Mysore from north to south, and of a width of about twenty miles. The main portion is about sixty miles west of the Kolar gold field at surface, but minor outliers occur up to within a mile of the boundaries of the schist belt.

The three parent granites connected with the above activities are all:

> . . . essentially composed of quartz and orthoclase, often with much microcline, whilst hornblende is present in all varieties, biotite being somewhat subsidiary in amount. Thus as a comprehensive designation, the term "Hornblende Biotite Gneiss" may be said to cover all individuals of the complex (H. A. Martin (25)).

The hornblende and a portion of the biotite of the various granites are likely to have been derived from the incorporation of the schists. There also

occurs an interesting "Magnetite Granite" ". . . containing the magnetite in 'nests' and to such an amount, to the partial exclusion of hornblende and biotite, as to impart to the rock characteristics of its own . . ." (H. A. Martin (25)) which may be a product of contamination by the digestion of ferruginous quartzite.

Construction of an east-west vertical section across any part of the Kolar schist belt would, in the present state of knowledge, be a difficult task. It appears likely that the simplest structure to be expected is a moderately broad synclinorium with a single anticlinal crumple in the vicinity of the Champion lode. There may be greater complications in the folding, and the entire picture has been modified through frequent stages of pre-mineralization thrusting, movement of an age contemporary with the introduction of much of the quartz, and post-mineralization faulting.

LOCAL GEOLOGIC ENVIRONMENT.

In the Mysore mine, and similarly in the other mines of the Kolar field, the metamorphic rocks are represented almost exclusively by the Dharwar series. Hornblende schist constitutes practically the entire formation.

In the vicinity of the lodes there occurs biotite schist interbanded with the commoner variety in thicknesses varying from a few inches to thirty feet. The only clues to the original structure of the flows are these persistent bands. They can be considered as distinct beds that have been laid down in the form of volcanic ash of more acid composition than the predominantly basic lavas. The biotite schist may originally have been tuff. Differing markedly from the rock types with which it is interbedded, the biotite schist retains its identity under the degree of metamorphism now apparent.

All types of schist exhibit a high degree of metamorphism and there is no trace of the original physical features of the flow rocks.

In the neighbourhood of the lodes the schists commonly have been impressed with an intense cleavage, the biotite variety being the more susceptible on account of the tabular nature of the dominant mineral. The most significant variation discernible, and one through which different types of hornblende schist may be distinguished, is this same susceptibility to shearing, and the ease with which the cleavage may be impressed upon it.

Distant from the lodes the schist assumes a more massive character, and is generally of a coarser grain. It has been observed that the schists exposed in the lower levels of the south end of the Mysore mine are more fine-grained than the average schists of the remainder of the underground workings of the field (23).

A common variety of hornblende schist encountered near the lodes is tufted amphibolite, in which the hornblende occurs as radiating aggregates. This may be taken as an indication of recrystallization under the influence of considerable pressure. The specific gravity of the less usual variety of schist is 3.15, while that of the average hornblende rock is only 3.08. (Figures according to H. A. Martin (25).)

The granitic rocks and the Champion gneiss are not exposed within the boundaries of the Mysore property. The most highly schistose members of the former group are more than two miles distant in either the east or west direction from the outcrop of the Champion lode.

The general configuration of the schist belt in relation to its associated rocks is shown in Fig. 1, and in particular the granitic divisions of the Mysore Geological Survey are distinguished.

The Dharwar System and the Champion gneiss here attain their maximum compound width of more than four miles from east to west. In the north and south direction the same band has been traced for more than fifty miles. It enters the territories of British India a mile beyond the southern boundary of the Mysore property.

Dikes of diabase of varying size, and attaining a maximum width of more than one hundred feet, are of later age than any of the previously mentioned rock types. The dikes strike in two main directions at right angles to one another: north-south and east-west. These intrusives may be assigned to phases of igneous activity of a deeper-seated character and subsequent age to the granitic intrusives. One or other series of dikes may have formed the feeder channels for the basic outpourings that formed the Deccan trap of Tertiary times.

Diabase of definite pre-Cambrian age is known in other parts of the State. It seems likely that the earlier and complementary system of dike intrusions was also of pre-Cambrian origin.

In order to obtain a representative idea of the constitution of the commoner hornblende schist in the wall-rocks of the Champion lode random samples were selected. These were taken from localities unaffected by the mineralizing fluids and are now described in detail.

One specimen comes from a point three hundred feet in the hanging-wall of the veins on the 55th level of the Mysore mine. It was found in the wall of the crosscut east from Edgar's shaft, and at a vertical depth below datum of approximately 4,000 feet.

This example of the hornblende schist is a compact, fine-grained rock whose schistose character is not readily apparent in hand specimen. The broken surface is greenish to black and appears micro-crystalline.

Microscopically the rock consists of an interlocking mosaic of common pale green hornblende, with irregularly distributed iron oxides and interstitial quartz and feldspar. The latter minerals are characteristically free from iron oxides.

The hornblende shows characteristic cleavage. This is distinctly curvilinear and bent or distorted in many instances. The mineral is highly pleochroic and shows no alteration. There is no alteration of any kind to be seen throughout the rock. There is a suggestion of a slight "bleaching" of the hornblende in small irregular patches.

The proportion of the major minerals is approximately:

hornblende	90 per cent
quartz	9 per cent
feldspar—under	1 per cent
iron oxide under	1 per cent

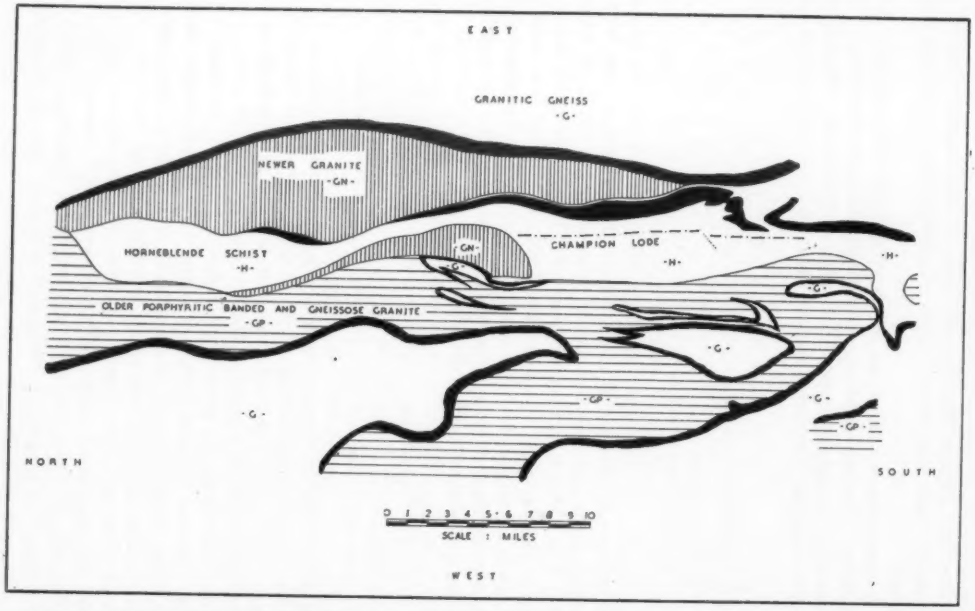

FIG. 1. Geological map of the Kolar gold fields and adjoining country, surveyed by the Mysore Geological Department. Conglomerate shown in black *within* the hornblende schist remnant. Reproduced from reference (11). Date: ante 1900.

A small amount of zircon may be seen. The plagioclase is an acid labradorite. The proportion of orthoclase to plagioclase could not be determined.

A second specimen is from a point seven hundred feet in the footwall of the lode on the 48th level of the Mysore mine. It occurred in the crosscut west from Edgar's shaft at a vertical depth of approximately 3,300 feet below surface datum.

This is a compact fine-grained, microcrystalline rock with a distinct cleavage and lineation. The broken surface is dark greenish-grey in colour. The mineral assemblage, paragenesis and distribution of species are identical with that in the first example, the proportions of the main constituents alone being different:

hornblende	75 per cent
quartz	24 per cent
feldspar—under	1 per cent
iron oxide under	1 per cent

Another sample was taken from a point three hundred feet in the hanging-wall of the lodes on the 76th level of the mine. This occurred near Rowse's No. 2 auxiliary shaft (an internal opening), at a vertical depth of approximately 6,000 feet. This is again a compact rock, of medium grain, and with the schistosity readily apparent. The appearance of the broken surface is variegated: black or very dark green, and near white. The same mineral assemblage and other characters are in evidence as in the other two specimens, but the proportions show a marked contrast:

hornblende	54 per cent
quartz	40 per cent
feldspar	5 per cent
iron oxides	1 per cent

Zircon and sphene appear as accessory minerals in minute amounts.

In the last specimen the hornblende shows some corrosion. An occasional fleck of dark biotite occurs, possibly as a result of interaction between interpenetrating fluids from the magma. The latter may have been at the stage of precipitation of biotite at the time of its farthest advance in the crust, *i.e.* coincidentally with the regional metamorphism. As an alternative mode of origin the biotite could be due to some original inequality in the composition of the rock, yielding a parallel with the biotite schist bands.

The steady decrease of hornblende as greater depth is attained will be compatible with the suggestion of F. K. Morris (personal communication, December 1938) that the Dharwars were originally all sediments, in which series limestones occupied a prominent place, and that they have been extensively altered by magmatic emanations.

The presence of isolated occurrences of biotite in the hornblende schists far removed from the lodes, as well as the fact that this mineral is a predominating feature in the fissure walls in many places where the crack carries no quartz, all point to the mica as an original constituent. It bears little relation to the passage of gold-bearing fluids.

A third and important variety of wall-rock is that to which the local name of *dogger* has been given. This is technically a micro-pegmatite gneiss, and of the same age as the Champion gneiss.

The common minerals in the latter rock, the *dogger,* are quartz, feldspar, and biotite, with subordinate pyrite and pyrrhotite derived from the vein-forming solutions. Hornblende occurs recrystallized after having been incorporated from the walls of the minor intrusive at an early stage.

The hand specimen exhibits pronounced cleavage and lineation. It is pale buff in colour, with distinct flakes of biotite aligned in the cleavage direction.

The intrusive *dogger* has been classified with the Champion gneiss by H. A. Martin (25), and variously termed "microgranite" and "felsite." Its specific gravity varies between 2.76 and 2.90; that of the schists is rarely less than 2.95.

It is believed that the *dogger* ascended along fracturing localized by the line of weakness coincident with the biotite schist horizon. It shows typically intrusive contacts and characteristic lenticularity. Although rarely pinching out altogether, the average width in different localities varies between two and ten feet.

The intrusive has been reported from the vicinity of the Champion lode throughout its length. From the fact that it occupies the same line of weakness and shear as the quartz veins it has come to be regarded as a valuable indicator of the close proximity of the east and west lodes when encountered in the lower levels of the mines. These two veins are found respectively near the foot-wall and the hanging-wall of the dike-like masses of dogger. It is likely that this previously formed rock of pegmatitic composition had the effect of bifurcating the plane of fracture when a renewal of fissuring took place.

Where the dogger is relatively wide the veins may in places be seen transecting the intrusive in the form of numerous parallel stringers of quartz. These occasionally coalesce to form one narrow vein.

It is noteworthy that the dogger in the Nundydroog mine at the northern end of the field is of considerably less average width than that in the Mysore mine. This would appear to be an indication that today's corresponding horizons in these two mines were at different depths, certainly under varying degrees of wall pressure, at the time of the intrusion of the dogger. The degree of pressure, and possibly the depth, were greater in the locality of the Nundydroog mine, where the intrusive was able only to attain a narrow width.

The dogger is thought to have been originally a pegmatite, but it could equally have been aplitic in texture, character, and origin.

DERIVATION OF LODE CHANNELS.

A persistent fracture zone crosses the full extent of the Mysore property from north to south. It has been traced an additional four miles in the former direction, through the Champion Reef, Ooregum, and Nundydroog mines (the latter including the former Balaghat), and for a farther two miles southwards. The lode fissuring thus attains a strike length that is known to approach a limit of ten miles.

Two main lines of fissuring have been mineralized in these mines; certain sections of each being termed the east and west lodes.

In the Mysore ground there is evidence of duplication of these veins at outcrop through the influence of a steep post-mineralization thrust that trends slightly west of north. The main workings of the mine are contained in the upthrust block, while the undisturbed sections have been developed to some slight extent from the Pilot shaft, which is 1,600 feet east of the main workings, and other small shafts of no present nor past productive importance. There is no evidence in the deepest parts of the main mine of this thrust plane

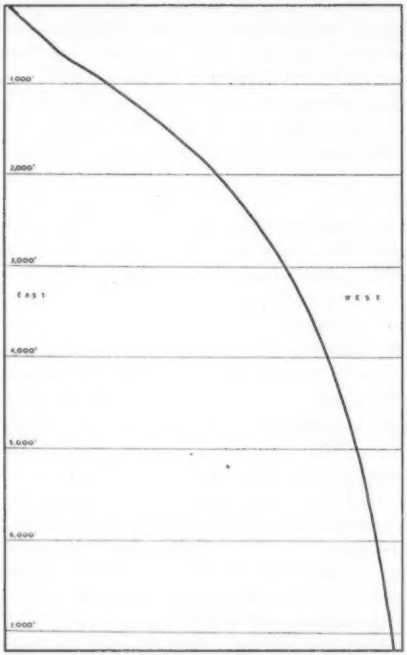

FIG. 2. Idealized section of the Champion lode, east branch, obtained after eliminating the effects of intra-mineralization shearing. Location within 500 feet of the southern limits of the Mysore mine workings.

or zone connecting the portions of the Champion lode there developed with that section exposed in the drifts off the Pilot shaft. The dislocation is unlikely to be met within the ultimate limits of mining.

The most logical explanation of the original openings along which it is inferred that silicothermal solutions have advanced freely to form the lodes is that they are tension fissures produced through the agency of torsional stress. The main components of the couple producing this regional stress are thought to have been oriented so that they were operative in the vertical plane.

The general form of the fracture plane or zone may be seen by reference to Fig. 2. This is a cross-section of the east lode obtained by the elimination of all effects produced as a result of intra-mineralization movements. Major regional forces directed vertically upwards at some points to the west of the lodes can be considered to have been complementary to others directed vertically downwards along a line to the east. The net result would then be a torsion fissure of the form shown on the cross-section.

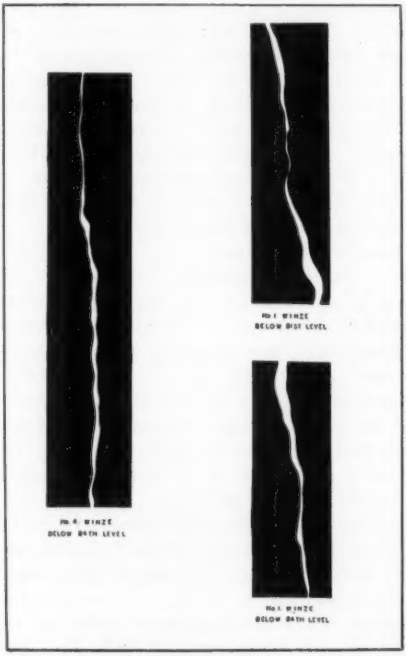

FIG. 3. Cross-sections of the Champion lode in the vicinity of the 8,000 feet horizon. Approximate depth of section: 125 feet.

In Fig. 3 have been reproduced cross-sections of shorter sections of the lode-fissuring that serve to emphasize the tensional character of the openings. The slight amount of displacement of opposite walls relative to one another is apparent. These lodes thus occupy tension fissures produced by torsional stress, in short: torsion fissures.

The general dip of the fissures is to the west. The angle of dip becomes steadily steeper with depth and is rarely less than forty-five degrees. In the early days of mining in the Kolar field there appears to have been uncertainty as to whether the ore bodies were veins or a "banket." Majority opinion at

that time held that the lodes would flatten in depth and C. M. Rolker alone held the view that they would steepen in depth, as they are now proven to have done ((12) p. 173—discussion).

In the deeper levels of the mines it is evident that the shearing or fissuring has been localized along a line of weakness defined by the band of biotite schist of greatest persistency. The pre-existing dogger in this same zone may be considered to have split the fissuring into two distinct planes or zones of shear, known as the east and west lodes. At no point does there appear to have been a great amount of movement along these shears or torsion fissures.

The presence within the hornblende schist formations of this biotite schist horizon is the reason for the unique localization of the vein system along these well defined lines. In the usual case, fracturing of this type is more nearly vertical *throughout* its extent, as evidenced by many examples in the Canadian shield areas. The dogger is an incidental intrusion occupying the same zone of weakness and shear. Its lenticular habit exercises a local control over the size and disposition of the fractures containing the quartz. Regional shearing in other parts of the world is often split along a number of localized planes by the presence of earlier intrusives of this nature.

The two main lodes of the Champion vein system are generally within ten feet of one another in the lower horizons of the Mysore mine. Approaching the surface they may be separated by more than one hundred feet of interlaminated hornblende and biotite schist, with the former predominant.

The main biotite schist horizon is neither so uniform nor so persistent as the surface level is reached. It begins to split into several distinct bands. At the shallowest horizons in the southern part of the Mysore property there has been a pronounced tendency for the vein-fissuring to break away from the structures that controlled its course in depth. This feature is well shown in Fig. 2 by the steepening of the lode in the last 500 feet of its course towards surface in the south end of the present Mysore workings.

West of the Champion lode system are other persistent veins. The most important of these are known as the West Balaghat and Oriental lodes. These are west of Munday's lode and east of the remaining Wolfe's and Lawrence's lodes.

The two first-named of the above group of veins are reported to contain a much greater quantity of pyritic material than the Champion lode. The Oriental lode in particular is stated to be highly pyritic. Their close proximity in source to sections of the batholith that had incorporated "iron formation" may explain the increased amount of iron mineral in these veins.

The average gold content of these minor vein systems to the west is indicated to be considerably less than that of the ore in the operating mines. Their dip is to the west so that it may be inferred that they occupy fissures of a similar type and produced by like forces to those that created the Champion lode system.

A petrographic examination of the vein material would be one essential prerequisite to any estimate of the possibilities in depth of these minor lodes. In any event it is probable that their more promising portions would not be due west of the ore shoots on the Champion lode but would be offset far to

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the north. It is suggested that they would appear at the intersections with these lodes of the intra-mineralization thrusts responsible for ore-bearing structures in the mines of the field.

A structural analysis of the entire schist belt and its immediately surrounding igneous masses would be the sole method of attack that could give positive indications of future worth in the lodes previously discovered but never developed.

DISLOCATIONS EARLIER THAN THE FINAL STAGES OF QUARTZ CONSOLIDATION.

A succession of steeply dipping strike thrusts cuts across the Champion zone of vein-fissuring at an acute angle that varies up to twenty-five degrees in individual cases. The acute angles of intersection of the thrusts with the veins face northwest. In every case the thrust plane is of a dip slightly steeper than that of the vein fissure at the point of intersection with the latter. With increasing depth the difference between the angles of dip lessens. At the 7,000-foot horizon in the Mysore mine, and at shallower levels in the other mines of the field, the dips of the thrusts and the veins rarely differ by more than five degrees.

The thrust system is contained within a broad band of a width amounting to at least seven thousand feet at right angles to the strike of the component planes of movement. Within this zone there have been more than a score of major dislocations of the vein fissure prior to, and during the processes of mineralization.

Owing to the acute angle of intersection of the zone of thrusting with the Champion vein system, the latter has been affected for a distance of almost five miles along its strike. This distance constitutes the productive portion of the Kolar gold field.

In most instances the movement along the thrust planes has taken place in as nearly as possible a vertical direction. The west side has always been shifted upwards relatively to the east or foot-wall side. The displacement of the vein fissures has thus always been to the north on the west side of the thrust planes. The displacement is most evident and obvious where the thrust and the vein fissure both dip at a low angle.

At depths below three thousand feet in the Mysore workings, and where the dips are within twenty degrees of the vertical, the horizontal and vertical displacements of the lodes appear of only small significance. With shallower dips the true vertical and apparent horizontal shifts attain a maximum of 150 feet.

Where the thrusts cut the vein fissures, drag-openings have resulted; intricate fracturing of the schists has taken place for some distance on either side of the intersection. The form and extent of the zone of disruption is determined by the amount of displacement, which in turn depends in part upon the angle of dip of the vein and thrust, and upon the physical properties of the enclosing rocks.

The drag-openings are characteristically wider at horizons of flatter dip, and these cavities have been favourable sites for the emplacement of the larger

masses of gold-bearing quartz. Fig. 4 illustrates one such unusually large body developed within three hundred feet of surface in the Mysore mine.

Typical examples of the effects of thrusting upon the subsequently consolidated quartz of the lodes are shown in Figs. 5, 6, 7, and 8. These are the *folds* for which this field is justifiably renowned.

The dimensions of the folds, in cross-section and in plan, are of the same order of magnitude. In Fig. 4 an inclined winze is shown following the quartz on the limb of a fold and gradually approaching the *trough* or *gully* as it goes

FIG. 4. Mass of quartz filling drag opening in the shallow levels of the Mysore mine. Plan approximately 250 feet in length.

deeper. A raise is also shown starting on the *nose* or *crest* of the complementary curve in the fold structure and following it for some distance above the level.

Development along corresponding lines of nose or trough has been a widely attempted practice, but one attended by practical difficulties. It was originated in the earliest times and revived at the present day.

Where the fold is of no very great dimensions, both the nose and the trough may be conveniently opened up in the same working face. Such an instance is shown in Fig. 9.

Certain characteristic forms assumed by the quartz masses under the structural influence of the early and continued thrust displacements are shown in Fig. 10. A study of these diagrams will make it clear that to maintain a development face upon the most favourable section of a fold constitutes no easy matter. There has been a pronounced tendency for the native miner, and even the European foreman, to follow subsidiary off-shoots of quartz if the development program is not subject to detailed supervision.

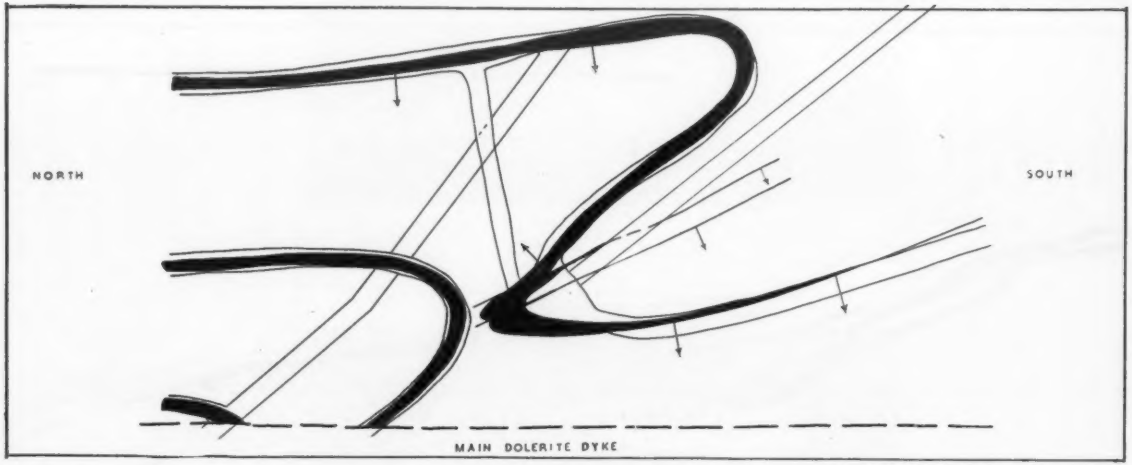

FIG. 5. Typical quartz structures produced by dislocation of the vein fractures along two parallel thrust planes dipping at a steeper angle in the same direction as the lodes. Development raise shown along the nose of the fold structure produced by drag accompany the thrusting.

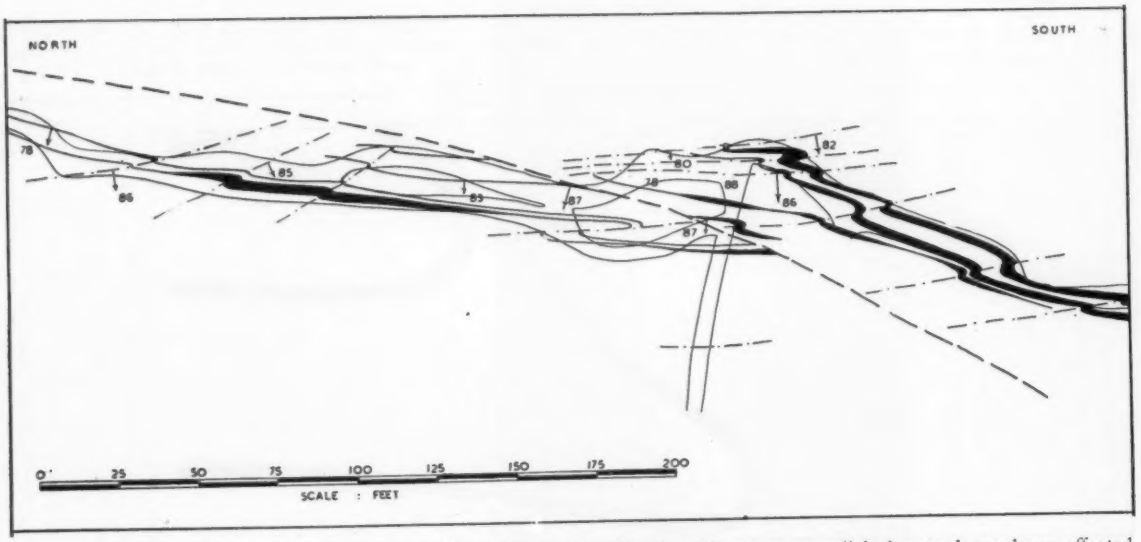

FIG. 6. Effects of drag openings on quartz disposition at deep levels. Numerous parallel thrust planes have affected the vein fracturing as well as a later strike fault (broken line).

The individual movements constituting the thrusting have taken place along single planes in many instances. In the majority of cases there are two major planes of movement to make up the full extent of one localized disturbance. Such an example may be seen in Fig. 11.

At one locality along the strike of the lodes the thrust movements are found to have been distributed over a large number of closely spaced and parallel gliding planes. Several composite thrusts in close proximity have been found to be of this nature.

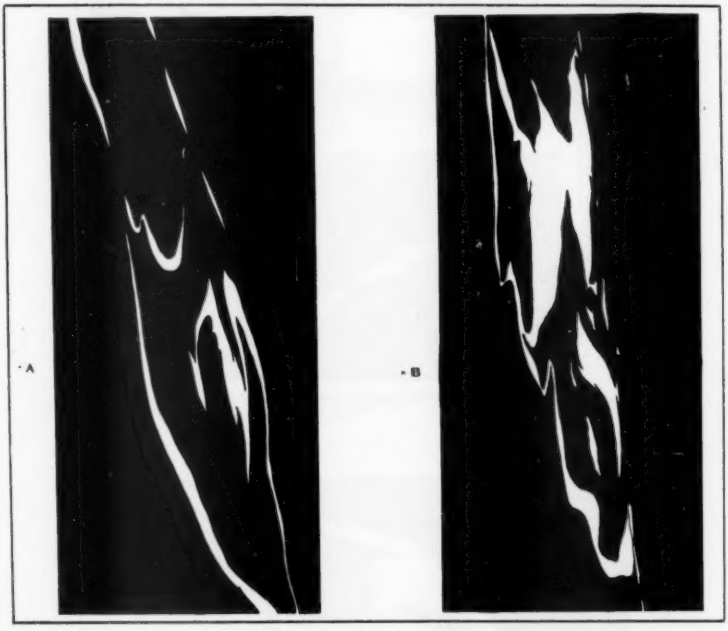

FIG. 7. Vertical cross-section of drag structures within the limits of drift height. 7,000 feet horizon.

Within the limits of compound thrust zones, even minute and impersistent stringers of quartz are of rare occurrence except along the main veins and in the drag zone adjacent to the planes of movement. Minor lenses of quartz are also only of sporadic occurrence along the thrust planes. Thus it appears highly probable that the thrusting occurred contemporaneously with the introduction of much of the quartz. Lateral pressure normal to the thrust planes continued throughout the process of mineralization, allowing little facility for access to the greater proportion of the strike length of these thrust planes.

Rare cases of the persistence of a minor amount of narrow quartz mineralization along the thrust planes adjacent to the lodes led to their designation as *transverse* lodes by Louis Stromeyer (private report ante 1900). Such an

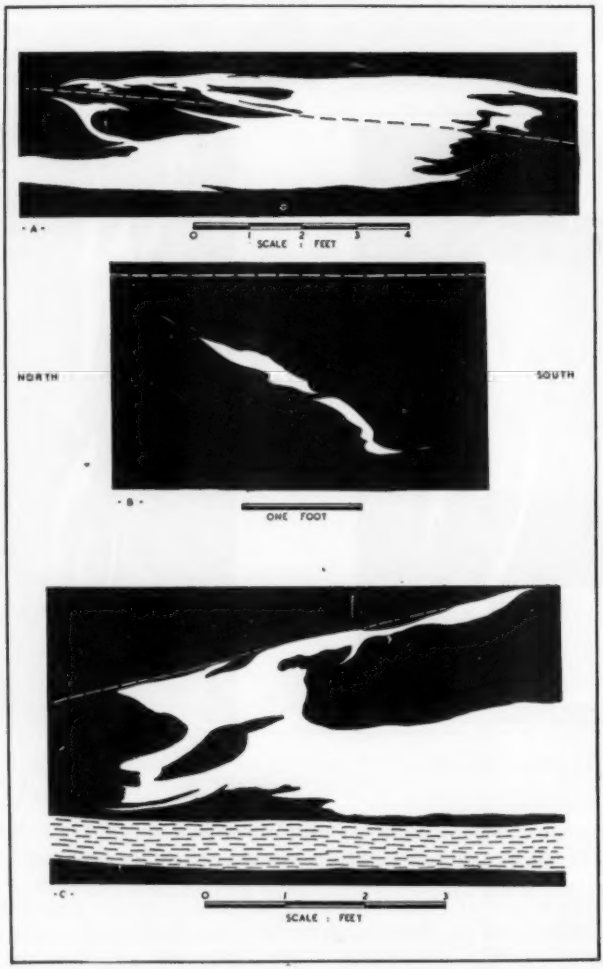

FIG. 8. A and C show quartz in characteristic drag openings adjacent to thrust planes at lower level horizons. B indicates torsion fissuring in the vicinity of a thrust plane (broken white line).

example was known as the "great transverse thrust line or Kempinkote lode" and occurs within the limits of the Mysore ground.

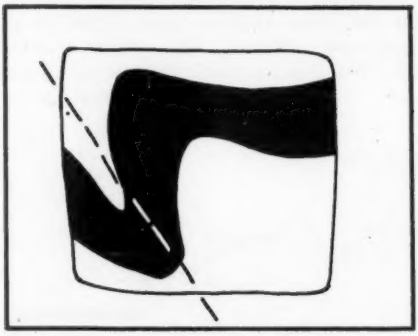

FIG. 9. Example of development along a small-scale fold. Raise above the 890 feet level south of Rowse's shaft and east of the great diabase dike.

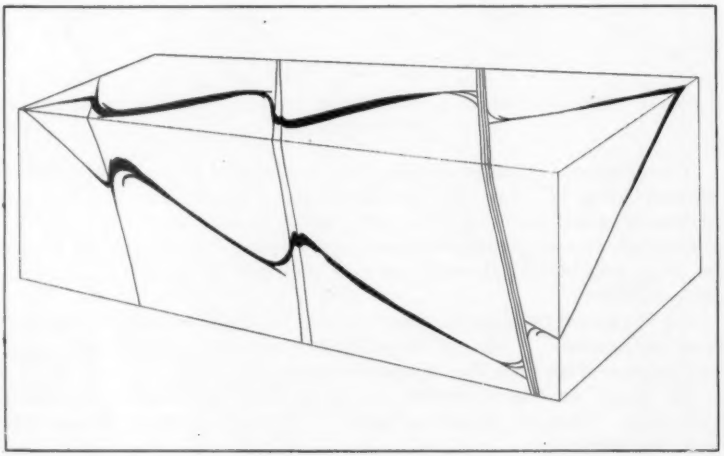

FIG. 10. Block diagram to show the various effects of intra-mineralization thrusting upon the form of the quartz along the line of the lode. Not to scale.

At the seven thousand feet level the thrusts have little effect upon the lodes in the Mysore mine, and one that is often fully apparent within the limits of a single drift width. Their structural effect upon inter-thrust stretches of the veins remains important, as will be indicated later.

In the Champion Reef and Ooregum properties thrust dislocations of greater magnitude persist to the lowest levels and are of considerable extent throughout these mines.

Figs. 6, 7, and 8, considered as a group, emphasize the difference in degree of magnitude of the ore bodies localized along "folds" as greater depths are reached in the Mysore mine workings. Fig. 6 shows several such folds within a limited distance and Fig. 7 is a vertical cross-section of similar complexities from the deeper levels. Both these examples are from the seven thousand feet horizon.

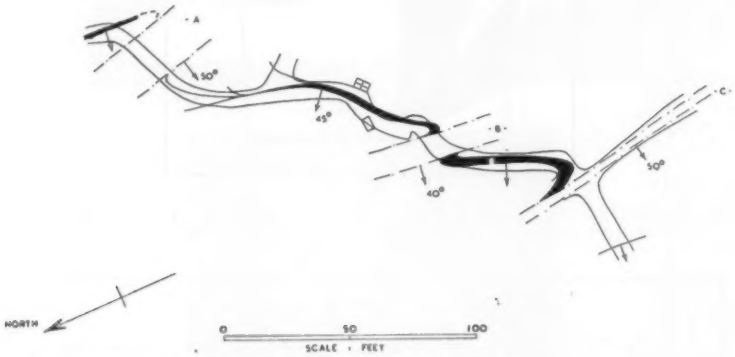

FIG. 11. Diverse effects of thrusting within a short distance along the vein. Deep horizons.

A longitudinal vertical projection of the vein system in the Mysore mine is exhibited in Fig. 12. The main structural features are the only ones that have been superimposed upon this view. The more important are the lines of intersection of the transverse thrust planes with the lodes. On the scale of the section, these lines on both the east and west veins are for the most part practically coincident.

The Pilot shaft developed a single shoot of ore localized along a transverse thrust intersection. It was cut off in depth by a transverse fault and a longitudinal thrust of later age than the mineralization.

The "folds" have been previously described by F. H. Hatch (11) and T. Pryor (23). They are considered by the former to have arisen through folding of the quartz:

> . . . there is no doubt that they are the result of enormous lateral pressure acting on the schist beds subsequent to the formation of the quartz veins, for the quartz in the folded portions of the veins has a peculiar banded and hornstone-like structure, which is the result of the great stress to which it has been subjected.

It is probably true to say that the vein material has been folded, while in a mobile state, but the quartz around the folds could not be distinguished from that along the straighter portions of the veins by any consistent or marked

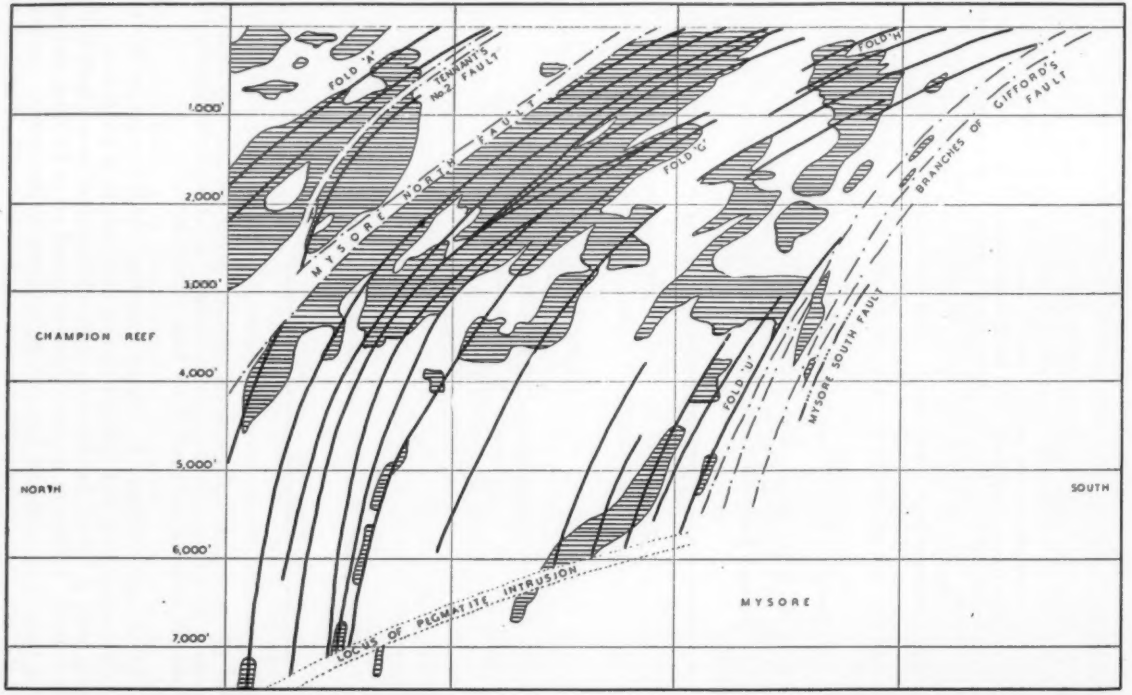

FIG. 12. Vertical longitudinal projection of the Champion lode in the Mysore mine workings. Shaded areas are the major ore shoots. Pitch lines of the main fold structures are shown in solid black.

characteristics. Hatch quotes the following description accredited to T. H. Holland (11):

Dark grey quartz with white bands and hornblende bands and lenses near the margin. Specimens show a tendency to break into irregular flat cakes through the prevalence of joint planes crossing one another nearly at right angles. Fracture away from joint planes, conchoidal with pitchstone lustre. Films of calcite along the best developed joints. Under the microscope the quartz is seen to be granulated to an excessively fine degree and trained out into bands almost as perfect as flow structure; nevertheless the parallelism of many grains gives an approximately simultaneous extinction over a large area. Thin long sheets occur with undulose extinctions, but crystallographically continuous across the two inch field. There are streaks and eyes of foreign minerals, hornblende, felspar, mica, and rods of tourmaline.

Pryor (23) confirms the views of Smeeth (20):

There are a few large zigzags which are usually called "folds" though it is probable that they do not represent the actual folding of a once plane sheet or vein of quartz and are more likely due to the filling in of zigzag or branching fissures or dislocations.

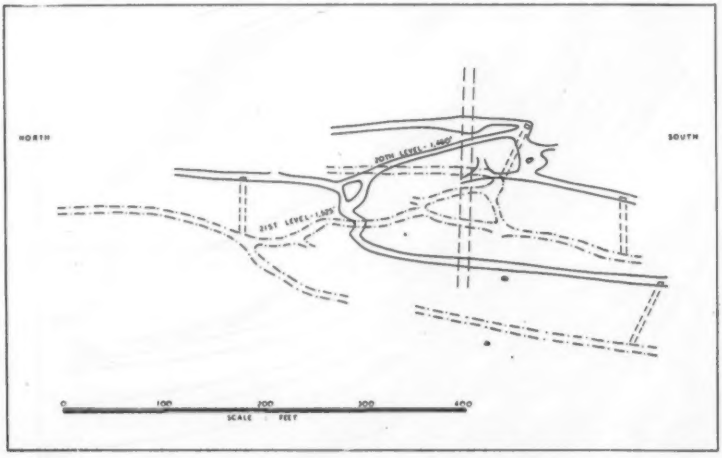

FIG. 13. To exhibit the parallelism of folds on the east and west lodes attributable to the influence of the same thrust plane. Development headings on the two lodes are joined by a drift along the plane of movement.

The "folds" were attributed to "zigzag fracturing" ((23)—reply to discussion); their association with dislocations thus first came to be recognized.

As a result of further detailed study these folds can now be said to have resulted from the infilling by quartz of fissures opened up in the drag zone attendant upon large-scale and powerful strike-thrust displacements. According to the local physical characteristics of the wall-rocks, so the shape, nature and extent of the fissure systems were controlled. The solutions were able to

effect a limited partial digestion of any fracture blocks encountered during their rise in the fissures under the influence of sub-crustal hydrostatic (magmastatic) pressure. The fluids were enabled to penetrate along the subsidiary fracturing that branched away from the main drag-cavities in many instances.

The parallelism of folds on the two lodes is well illustrated in Fig. 13. This is a plan of two consecutive levels in the northern section of the Mysore mine. On these two levels it chanced that the transverse thrust; which had been responsible for the formation of the folds, was investigated by development headings between the two lodes. The thrust was found to connect corresponding folds on the two veins and thus provides *prima facie* evidence of the true nature of the relationships.

Underground mapping on an appropriately large scale to provide adequate detail was completed in numerous other areas and the intimate connection between folds on one lode and those on the other was distinctly shown. The line or lines of thrusting coinciding with the steep central limb of the folds on either lode are always seen to be clear projections and extensions of one another.

GOLD-QUARTZ MINERALIZATION.

Petrographic Characteristics of Lode Quartz.—Specimens of vein quartz from different horizons were studied in thin sections. These appear to fall into two categories:

(1) medium-grained quartz mosaic wherein all the crystals are of the same order of magnitude. There is no evidence of strain polarization.

(2) an aggregate of elongated medium-grained quartz crystals exhibiting varying degrees of strain polarization. A proportion of the field is occupied by an interstitial quartz mosaic of much finer grain, possibly averaging one-tenth the lineal dimension of the larger crystal units.

Quartz of the first type is almost entirely confined to the wider portions of the individual veins. Character specimens studied came from the vicinity of folds at shallow horizons, from a composite stringer zone at intermediate depth, and from the central section of a four-feet wide vein at the 7,000 feet horizon.

The second type of occurrence, if it may be designated as distinct in habit, occurs mainly (but not exclusively) in the narrower, more frequently the straight sections of the veins. The samples were from lesser vein widths at shallow depth, from a two-inch stringer on the 7,000 feet horizon, and from a late transverse quartz vein within 1,000 feet of surface.

Either class of quartz may be auriferous, but it is highly significant that the elongated quartz units of early stage crystallization in class (2) are always free of metallic minerals and gold. These are confined to the fine-grained groundmass. In examples of class (1), the gold and the greater proportion of the metallics occur exclusively along the sutured contacts of the individual quartz crystals.

From the majority of the observations it may be inferred that the gold and other metallic minerals crystallized later than the main proportion of the quartz represented by the larger-size crystal fabric.

Visual inspection of acicular tourmaline crystals in place in a vein on the 7,000 feet horizon shows a very distinct preferred orientation in the plane of the vein. These crystals are several inches in length and possess a vertical attitude. A petro-fabric diagram of the quartz from the same section of the vein is reproduced in Fig. 14. This confirms the attitude preference shown by the tourmaline, although not in such a marked degree as the more highly

FIG. 14. Petrofabric diagram of vein quartz from the 7,000 feet horizon showing marked degree of preferred orientation.

susceptible tourmaline crystals occurring as isolated units. All the tourmaline is of early crystallization, whereas a part of the quartz became consolidated after the tourmaline and probably when the forces responsible for the orientation described had already been dissipated, or otherwise become inoperative.

Quartz from all sections of the Mysore mine contains numerous dusty inclusions. It is notable that the fine-grained matrix contains many times the quantity of inclusions found in the larger-scale mosaic. Both clear grey and white milky quartz occur throughout the extent of the veins. The latter type shows more persistence through the lower levels, while it is comparatively rare at upper horizons. The change from one type of quartz to the other takes place gradually as the veins go to greater depth. If the milkiness is caused by

an abundance of gaseous inclusions, then it is reasonable to conclude that a great many of these will have had opportunity to escape into the wall-rocks as higher horizons are attained. This affords a reasonable explanation of the progressive change through from milky quartz to the clear variety as the surface is approached.

Determinations by the author and by V. B. Meen (University of Toronto —private communication per E. Y. Dougherty, 1938) were to the effect that much of the quartz from these veins is of the "low-temperature" variety, *i.e.* it must have crystallized below the temperatures shown in Table I for the quoted depths below surface at the time crystallization took place:

TABLE I.

INVERSION TEMPERATURE OF QUARTZ AT VARIOUS DEPTHS IN THE EARTH.
Assuming an average density of 3.0 (R. E. Gibson—29).

Depth in km.	Pressure in megabaryes (approx.)	ΔT in ° C.	Temperature of inversion in ° C.
0	0	0	573
1	300	7	580
5	1,500	33	606
9	2,700	63	636
10	3,000	71	644
20	6,000	(157)	(730)
30	9,000	(259)	(832)
40	12,000	(376)	(949)
50	15,000	(509)	(1082)

Note: figures in parenthesis are interpolated.

The simple twinning characteristics of the "low-temperature" variety of quartz are clearly brought out through etching with hydrofluoric acid.

Paragenesis of the Lode Minerals.—The non-metallic minerals occurring in the veins, apart from the quartz, include tourmaline, albite, and late carbonate. The commoner metallic minerals are pyrite, pyrrhotite, galena, chalcopyrite, and native gold. The latter do not aggregate more than one per cent of the ore.

Albite and tourmaline have been observed at widely varying horizons in the vein system. The albite is decidedly more common in depth. The tourmaline occurs in characteristically larger crystals in the deeper sections of the veins, by contrast with the felted aggregates of minute needles seen at shallower horizons.

Tourmaline has in every case crystallized early and has frequently suffered cracking and partial redissolution, both of individual crystals and of aggregates. This mineral has thereafter been veined through by the subsequently crystallizing quartz, and occasionally albite.

The albite is considered to be earlier than much of the quartz, but later than the tourmaline. These three minerals invariably exhibit a close association. There is often a suggestion of attempted euhedral form on the part of the albite. This type appears within the cracked tourmaline in some places where albite occurs to the exclusion of quartz in local areas. Examples of fractured

albite crystals veined with quartz prove conclusively that the latter was continuing its crystallization after the consolidation of the albite.

The albite has been determined by V. B. Meen (private communication per E. Y. Dougherty—1938) to be of the same variety as that occurring in the later pegmatites. There was consequently some doubt thrown upon the conclusion that albite (and some of the tourmaline) in the gold-bearing quartz had been deposited from the same solutions. It was suggested that the felspathic material, in particular, was a later injection into the auriferous quartz veins. It has been concluded as incontrovertible that the albite was deposited from the same fluids that formed the quartz veins and the gold, and for the following reasons:

(1) the intimate relationship exhibited by quartz, albite, and tourmaline, throughout the range of deposition.

(2) the quartz-tourmaline-albite association in the deeper portions of the vein system has been seen to occupy zones at distances of more than fifty feet from any known body of later pegmatite. In the shallower horizons, this same mineral association occurs thousands of feet from known pegmatite dikes.

(3) the felspathic portion of the deeper vein horizons is confined to the central part of the fissures. If this were introduced with the later pegmatite intrusion this phenomenon would imply refracturing along a central line. All the pegmatite observed in close spatial relationship with the vein-quartz has been injected along the contacts or obliquely across the quartz bodies. Shattering of the intermediate sections of the veins is nowhere evident, and would be unreasonable in view of the natural planes of parting at either margin.

(4) the vein specimens subjected to most intensive study were taken from a comparatively high-grade section, the assay in gold at that point, and for some fifty feet in any direction in the plane of the vein being over an ounce to the ton. Having regard to the relative proportions of the felspathic and quartzose material, if there had been any dilution as a result of the intrusion of later pegmatitic material, the original grade of the quartz would have been between two and three ounces. Such a grade would almost certainly imply some visible gold, but none was observed nor reported from this section. The pegmatites are barren except in the immediate vicinity of auriferous veins, where they have sometimes incorporated a slight amount of gold-bearing quartz.

(5) the particular vein specimen mentioned under (4) was from the deepest developed horizon (1938) in the Mysore mine, *i.e.* deepest in relation to comparative levels of deposition, but not so deep with reference to the present surface as some other developed sections of the Champion lode. Assuming the gold-quartz veins and the pegmatites to have been comagmatic, as other evidence would indicate, but only separated in time by the event of shear-fracturing to admit the pegmatite intrusions, then a similarity in composition for the two types of material is not an improbability.

(6) muscovite is extremely rare in the vein quartz, and garnet is unknown. Both these minerals are common in the pegmatite but unknown in the felspathic portions of the lode.

(7) in thin sections the texture of the pegmatite is characteristically of a granitic or pegmatitic habit, with the quartz often subordinate to the feldspar. In contrast, the felspathic material of the gold-quartz veins shows quartz considerably in excess of the feldspar. The latter occurs chiefly as crystals intermediate in size between the first and second stage quartz. It forms a proportion of the groundmass, being in part medium-grained, but showing also in the interstitial fine-grained aggregate. The feldspars have suffered a marked

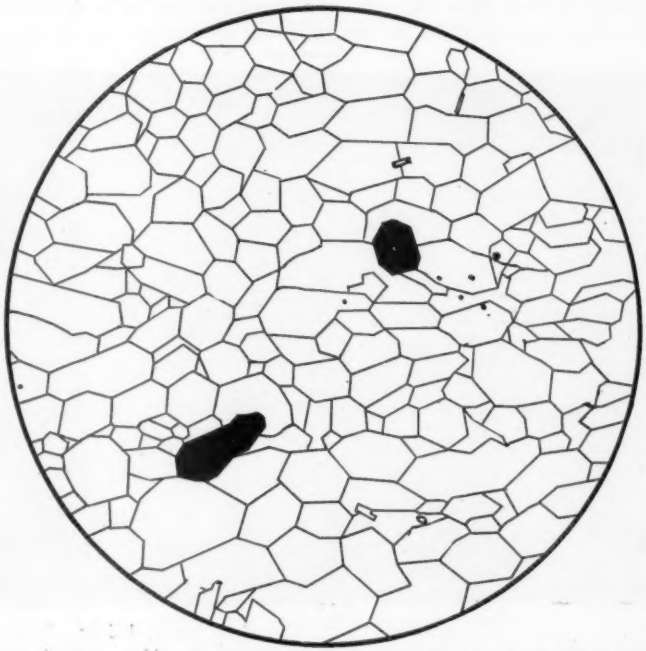

FIG. 15. Black areas show examples of crystalline gold in quartz mosaic. Rare. Approximate diameter of crystals .01 in.

degree of corrosion and the pattern of the entire section was suggestive of this same process having affected the quartz of early crystallization. The fine-grained groundmass appears to be the result of a final rapid stage of consolidation.

(8) the presence of a sulphide (probably pyrrhotite) in intimate association with the felspathic material of the veins aids in distinguishing its genetic affiliation from that of the pegmatite. No sulphides have been credited to the pegmatites in this area.

(9) triple zoning of the tourmaline in the felspathic vein-quartz was in distinct contrast with the faintly evident incipient zoning in the tourmaline of the pegmatites.

The foregoing reasoning would suggest that the Champion lode will be found to grade from a predominantly quartz-filled system of veins into a pegmatite swarm as deeper horizons are attained. This circumstance is comparable with that suspected in other parts of the world.

It is submitted that the early deposition of tourmaline, feldspar (albite) and a proportion of the quartz occurred during the time that *silicothermal* (48) solutions were in ascending motion through the vein fissures. When flow ceased due to blocking of the upper sections of the fissures by tectonic movements, crystallized material, or from whatever other causes acting alone or in

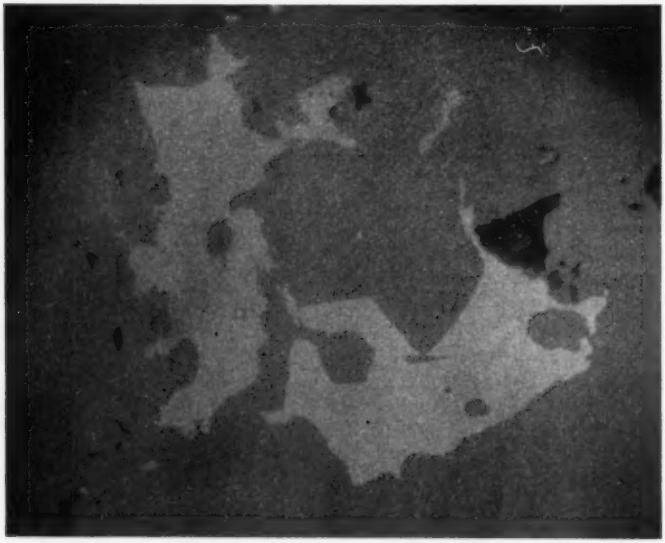

FIG. 16. Gold area (white) in quartz (grey) by reflected light. Black areas are pits, probably left by remnants of mica becoming removed during polishing. Cross-section (basal) of quartz crystal in center field is .003 in. in diameter.

combination, then a pressure was built up and a certain amount of the early crystals were temporarily taken into solution again. Cracking of existing crystals frequently occurred and elongation of some of the quartz grains resulted from selective dissolution and redeposition at points of reduced pressure. Cessation of movement also eliminated any further access of heat and a rapid loss to the wall-rocks brought about the final rapid crystallization of the interstitial quartz fluid as a fine-grained mosaic in which was retained the metallic content of the residual solutions.

Gold has been observed in the form of an almost perfect rhomb-dodecahedron, Fig. 15. Pyrite has also been seen as good pyritohedra. At the same time it must be emphatically stated that it is much more common for both gold

and pyrite to be present as crystallizations of later date than the quartz. Similar time relationships are shown by the other metallic minerals. Fig. 16 is a photograph of a polished specimen of the auriferous vein quartz. It shows clearly the habitual later relationship of the gold to the quartz gangue.

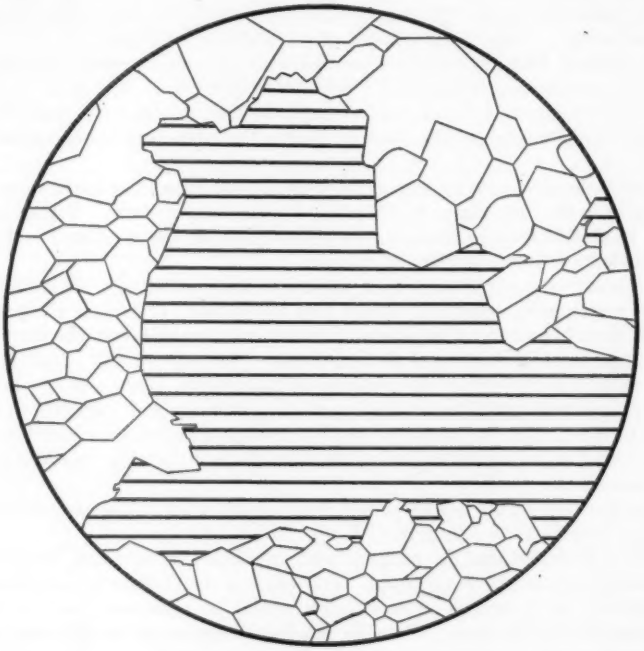

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FIG. 17. Normal relationship of metallic minerals to quartz. Shaded area is pyrite. Pronounced euhedral character of quartz to be noted.

A drawing made from a slide to show the normal relationship of the quartz to a metallic mineral, in this case pyrite, is reproduced in Fig. 19. The pyrite appears to have been the earliest sulphide to crystallize, and the commoner metallic minerals have followed it in this order of crystallization: pyrrhotite, galena, chalcopyrite, and lastly *gold*.

Wall-rock Alteration.—Although the gold values throughout the Champion lode system are confined to the material of the veins, a brief description of the more important features of wall-rock alteration is not without interest. A comparison with other deep-seated gold occurrences may thus be made, and has already been done in the case of Porcupine and Kirkland Lake (45).

The elements introduced into the enclosing rocks in largest amount have been sulphur and silica. There is little other new material apart from carbon

dioxide, but there have been achieved certain characteristic reactions between the vein-depositing fluids and the country rock.

Sulphur has combined with the iron of the magnetite and ilmenite to yield pyrrhotite. Silica is a mineral of very general introduction and occupies much interstitial space between the original hornblende and the other products of reaction and alteration. Quartz has also penetrated the wall-rocks through localized zones of minor gash-veinlets of no economic importance.

Hornblende and ilmenite have reacted with the vein-forming solutions to contribute sphene, pyrrhotite, and a pale green pyroxene. Migration of lime from the hornblende has taken place towards the vein fissures, and enters epidote or calcite after all the available titania has been used in the formation of sphene.

Carbon dioxide, next to sulphur and silica, is an important addition to the wall-rocks in the immediate neighbourhood of the vein contacts. Where there was a local deficiency of alumina, the carbon dioxide has combined with the lime to yield carbonate in place of epidote.

The occurrence of pyroxene as a product of reaction between the amphibole and the mineralizing solutions, noticed first by Smeeth (15) where the granite invades the schists, can be considered thoroughly compatible with the distinctly high-temperature affiliations of these deposits. The nature and temperature-depth class is evidenced by the presence of tourmaline, albite and pyrrhotite, the environmental attributes, the high grade of metamorphism exhibited in particular by the hornblende schists or amphibolites, and the extreme likelihood of elevated crustal temperatures during the time the vein-forming solutions were being introduced.

Pyroxene has rarely been reported from quartz veins. The only previous reference noted was by Lindgren (7).

It is to be noted that the country rock in which this vein was found is a granodiorite containing hornblende. The veins of the Allegheny gold district in California occur in part in hornblende schists but pyroxene has not been mentioned in the literature. Possibly the temperature was insufficiently high at the time of vein formation for the reaction to take place.

Mention should finally be made of the subordinate amount of chlorite and sericite in the wall-rocks of the Champion lode. The comparative scarcity of these minerals indicates that a relatively dry melt was responsible for the mineralization. The small amount of sericite also reflects in part the scanty feldspar in the hornblende schists. The existence of the latter alteration mineral depends on the proportion and presence of the feldspar in the originally fresh wall-rock.

In a comparison of the wall-rock alteration at Kolar with that at Porcupine and other localities where there are veins of this deep-seated class, it can be seen that the differences in reaction products are due mainly to the variation in composition of the original wall rock material.

Thus at Porcupine there is an absence of pyroxene, and a relative scarcity of sphene and epidote, owing to the absence of hornblende and ilmenite in the country rock.

Sericite is scarce at Kolar on account of the feldspar deficiency in the am-

phibolite. Pyrrhotite, and possibly a minor amount of biotite of secondary origin, as well as the diagnostic albite at Kolar, may denote a higher temperature, either of environment, or the mineralizing solutions, or both. The contrast is to be made with those fluids that have introduced abundant pyrite, chlorite, and sericite at Porcupine.

The vein forming fluids were, strictly speaking, not so obviously hydrothermal as *silicothermal* (48).

POST-MINERALIZATION DISPLACEMENTS.

The relative positions of the different veins have often been changed considerably since the emplacement of the quartz and its crystallization. Factors responsible for these changes may be classified into: (1) thrust movements (reverse faults); (2) normal faults; (3) pegmatite intrusives; (4) diabase intrusives.

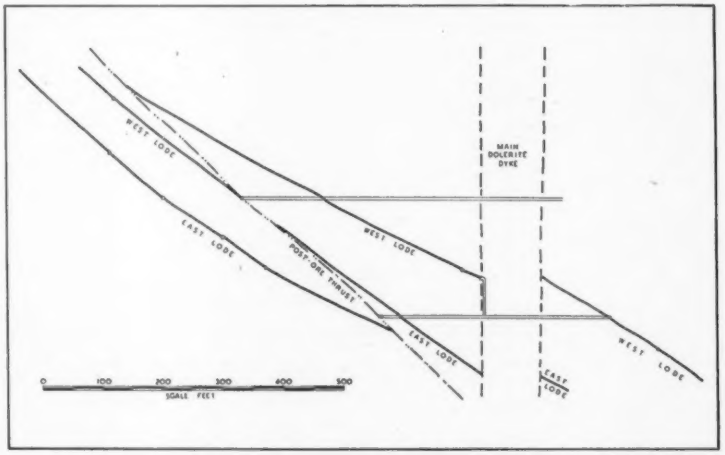

FIG. 18. Vertical cross-section to show dislocations of the lodes by post-mineralization thrusting and diabase dike intrusion.

Thrust movements have been such as to bring about the apparent existence of three and four separate veins on the one level of the mine. Termination of a vein in depth on the footwall side of the thrust, when the latter is of steeper dip, is conclusive evidence of the true nature of the relationship.

A cross-section of one example of the thrust-displacement of the veins is shown in Fig. 18. The movement affected both the east and west lodes. Pressure and transposition along some of these thrust planes, as well as the ingress of very small quantities of residual fractions of the mineralizing solutions, have often been sufficient to bring about the recrystallization of the hornblende to pyroxene and biotite through the agency of heat. Thus a mineral

assemblage similar to that in the walls of the veins is sometimes seen. On this account the lines of such thrusts were at times termed "lode formation." Much money was lost in years past through expenditures in abortive drifting along such lines in search of ore.

Alteration of the hornblende adjacent to the veins only took place when there was introduction of quartz at high temperature. Recrystallization adjacent to planes of movement was possible through frictional heat without the introduction of vein material. Completely unmineralized sections of the vein fractures are often indistinguishable from many other lines of shear where the movement has been small, and the ensuing alteration slight.

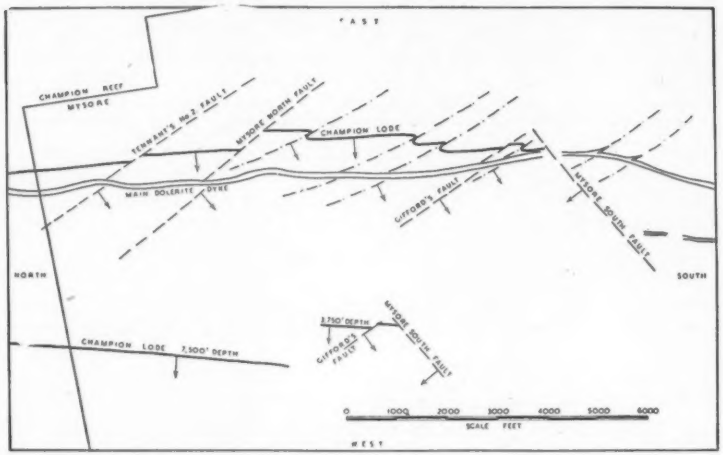

FIG. 19. Recapulation of important tectonic movements within the Mysore mine property. Dot-dash lines are representative of numerous intra-mineralization thrusts of identical character.

Serious fault disturbances in the Mysore mine workings are four in number. These are all indicated in Fig. 19, which is essentially a recapitulation of all tectonic movements within the limits of this property.

A large scale plan including two of these faults is presented in Fig. 20. From north to south of the property the dislocations have been known as: Tennant's No. 2 fault, Mysore north fault, Gifford's fault, and Mysore south fault.

The Mysore north fault has been the one subjected to the most intensive study. All are normal faults and the main movement has been in the vertical direction in each case. Later and less important lateral displacements are also evident.

The vertical nature and direction of the main rupture is inferred from the present space relationships of the lodes on either side of the faults on successive levels. This is especially well illustrated in the case of the Mysore north

fault. In the latter instance the apparent horizontal displacement of the veins at surface is of the order of 500 feet, decreasing steadily until it is less than ten feet where the dip of the veins is within five degrees of the vertical along the bottom levels of the neighbouring Champion Reef mine.

Tennant's fault joins the Mysore north fault in depth. These two parallel Gifford's fault, striking approximately northwest and dipping southwest.

The Mysore south fault, on the other hand, represents a relief of stress in the complementary shear direction. It strikes northeast and dips southeast.

The age relationship of the two fault systems is not conclusive. Faulting terminates the presently productive portion of the Kolar gold field. In this

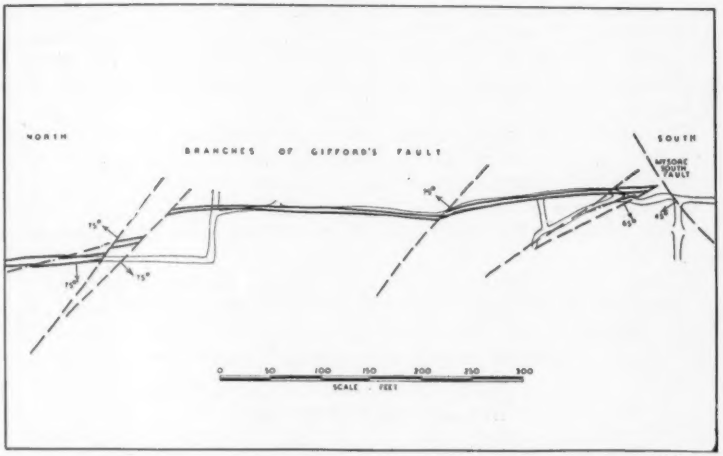

FIG. 20. Post-mineralization fault relationships. Mysore mine.

both Gifford's and the Mysore south fault are involved. It has to date not been possible to determine the amount of displacement caused by the latter, nor the relative importance of the two ages of movement.

Minor cross-faults with throws of a few feet are of infrequent occurrence and afford no serious detriment to the development of the veins.

An interesting strike fault affects the veins between the 6,600 and 7,100 feet horizons on the Mysore mine. This appears in Fig. 6. Another fault almost paralleling the strike of the lodes exists between folds *g* and *h* (Fig. 12) and displaces the southern part of the mine downwards to the extent of approximately 400 feet. The lateral movement has been negligible.

Intrusive veins or dikes of pegmatite of later age than either the *dogger* or the quartz veins were encountered below the 6,000 feet level of the Mysore mine. The main channel of pegmatite entry is an irregular thrust plane having a strike approximately thirty degrees east of north and dipping at a flat angle to the northwest.

The movement along the thrust-fracture has caused a shift of the veins to a maximum distance of fifty feet horizontally at right angles to their strike.

Offshoots from the main pegmatite zone have often followed along one or both walls of the veins where the latter have been intersected by the main channel of intrusion. Other branches of the pegmatite have followed courses of an erratic nature in the vicinity of the major intrusion. There is thus a zone of exceedingly disturbed ground between the 6,000 feet horizon at the south end of the mine and the 7,500 feet level at the boundary with the Champion Reef property to the north.

The zone of scattered pegmatite intrusions extends in the direction of the dip of the veins for several hundreds of feet. It renders the development of the lode within its limits an extremely difficult task.

The largest of any of the intrusives in the mine workings is a north-south dike of diabase (dolerite) that cuts the veins at shallow depth and traverses the entire length of the Mysore mine property. It extends across those of the neighbouring companies as well.

The diabase dike averages more than one hundred feet in width but produces little complication in the development of the ore. The straightforward nature of the dislocating influence may be seen by reference to Fig. 18.

Offshoots of the main diabase dike sometimes intrude along the walls of the veins, separating the quartz from its more usual hornblende schist neighbour.

Several smaller dikes parallel the great dike, and others at right angles to the veins have been observed throughout the underground workings. None of these approaches the size of the larger north-south dike. Tremolite and calcite are an occasional contact development in association with these intrusives.

LOCALIZATION OF ORE SHOOTS.

Structural Influence upon Economic Widths of Quartz.—The Mysore mine, and the Kolar gold field considered as an entity, present one of the clearest and most excellent examples of the influence of structural control in the formation of important bodies of gold-bearing ore material.

Numerous large masses of ore in extensive and persistently recurring shoots owe their economic width to simple mechanical principles. Crustal forces acting upon the variously bounded wedge blocks have been effective in opening up chambers for the introduction of auriferous quartz.

The grade of ore may be ascribed to the coincidence of the timing of the large-scale regional shearing to admit mineralizing fluids, with the availability in the magma reservoir of solutions containing gold concentrated from the magma through differentiation.

Reference should be made to Fig. 21 to attain an understanding of the interplay of forces exerting a dilationary influence upon certain sections of the vein fissures.

Strike-thrusting occurred before the quartz had completely crystallized, and it is probable that the movements started before the quartz-bearing fluids had been introduced.

The intersections of these thrusts with the vein fissures pitch north at an ever-steepening angle in the plane of the lode. They become almost vertical in the bottom levels of the mines. The pitch of the ore shoots parallels the intersections (Fig. 12) and each of the latter is almost without exception the locus of a more or less continuous pipe or "gully" of ore.

The relative movement along successive thrust planes of appropriate attitudes has often been such as to permit the introduction of silica-depositing solutions along the whole length of the vein fissures between the two planes of transverse movement.

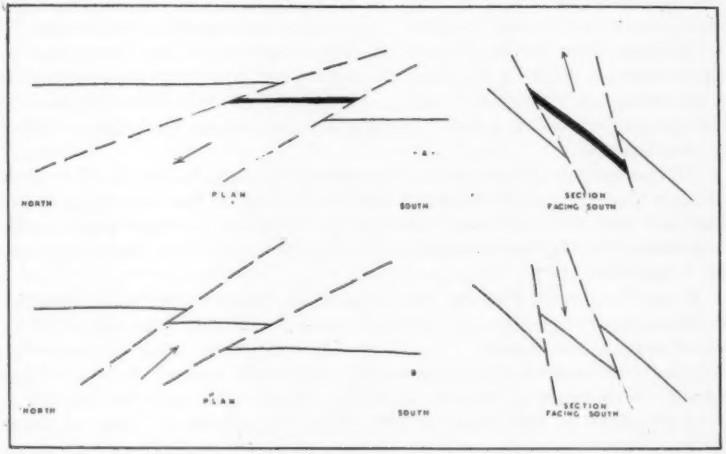

FIG. 21. A, relationship of vein fissuring and intra-mineralization thrusting favourable to the introduction of quartz. B, relationship of vein fissuring and intra-mineralization thrusting unfavourable to the introduction of quartz. (Vein fissure shown by solid line; thrusts by broken lines.)

In opposite cases, the relative movements have had the effect of wedging the hanging-wall of the fissures more tightly against the foot-wall and inhibiting the entry of mineralizing fluids. The potential locus of deposition in these instances remains a closed and barren fracture.

In considering a length of vein fissure isolated between two pre-mineralization thrust planes, it will be understood that mineralizing solutions will only be permitted entry along the fissures if the hanging-wall block of country rock is allowed to move away from the foot-wall section. Such a favorable case is shown in Fig. 21 (A). This condition is only fulfilled when the thrust planes, as viewed in both plan and cross-section, diverge into the hanging-wall. Lateral pressures then force the hanging-wall block upwards and away from the foot-wall in the direction of easiest release, *i.e.* towards the earth's surface. Opening of the fissures permits the introduction of economic widths of quartz filling.

The unfavourable situation is shown by Fig. 21 (B). The thrust planes

converge into the hanging-wall. No movement of the hanging-wall block away from the foot-wall is possible. The hanging-wall section becomes firmly wedged between the convergent thrust planes and the foot-wall mass. There is then no opportunity for the introduction of mineralizing fluids and no possibility of vein formation. Impersistent stringers of quartz and quartz-calcite are the sole evidence that fluids achieved penetration in the vicinity.

Between the two extreme conditions described above there can be an infinite variety of intermediate conditions. Thus the degree and extent of quartz deposition shows many stages. Changes in the relative dip and strike of successive thrusts cause the ore bodies, or quartz-filled sections of the fissures, to pinch or swell in depth as conditions vary from unfavourable to favourable.

In many cases the inter-thrust ore shoots have been found to persist for many hundreds of feet in the direction of the pitch of the fracture intersections before dying out. Similarly a barren section of the vein fissure may give way eventually to a shoot of quartz of economic width, revealed only by probing at greater depth.

The persistence of wide or narrow sections of quartz in the direction of the pitchline depends entirely upon the interrelationship of the controlling thrusts that limit each section of the fissure in two directions at right angles to the pitchlines of the fracture intersections, *i.e.* the junction of the vein fissures and the thrust planes.

It had been noted that the vein immediately above or below an important ore shoot was frequently of a stringery nature. This is what might be expected since at the boundaries of such a shoot the controlling conditions are changing from unfavourable to favourable and slight movements of the hanging-wall block begin to become possible. Narrow fractures are opened up along the planes of vein shear and the schistosity, and narrow zones of quartz stringers can be formed. As the movement of the hanging-wall block increases, the fissures allow widths of quartz up to thirty feet and more to be deposited.

Pryor (23) declares that the:

> . . . ore shoots have probably been caused by some structural feature in the fissuring

and further, that a:

> . . . study of the schists and felsites (*dogger*) has revealed no variations in the wall-rocks, which would account for occurrences of these shoots of ore, separated by stretches of barren ground.

The structural control is now indicated to be of paramount importance, and of a definite and recognizable character. It transcends in importance all other factors to which may have been assigned the contributory functions in the control of deposition of auriferous quartz lenses.

Distribution of Gold Mineralization.—The distribution of gold values within the shoots of wider vein material is so widespread that it has been difficult to appraise the factors that affect its localization. That there is localization becomes obvious when the wide variation of individual assays of quartz are taken into account.

It may be stated as a reasonably consistent generalization that the vein material in the neighbourhood of a *fold* is frequently of better grade than the material intermediate between neighbouring thrust planes and along the straight portion of the lode.

More than ninety per cent of the tonnage of vein filling contained in fold structures in the Mysore mine constitutes ore.

The reason for the diversion of a large proportion of the gold, originally deposited or separated from the silicothermal fluids, towards the fold structures is likely to be found through a study of the redistribution of values that takes place before the *late* crystallization of the metal, and while it retains a state of mobile fluidity.

Pressures of readjustment cause late refracturing of the newly crystallized quartz and movement along the thrust planes permit a certain degree of tensional dilation in the vicinity of the folds. The straight portions of the veins are subject only to direct pressure and constitute zones of compression. Thus there may be a tendency for the fluid or mobile metallic residual fractions to migrate from zones and areas of compression to those zones of incipient tensional dilation around the bends of the fold structures.

In a similar manner, any minor irregularities and cross-fracturing at points along the straight run of the veins may become potential zones of dilation under localized tensional stresses and become abnormally enriched with regard to the metallic minerals, and in particular: *gold*.

Folds and local structures affect the late redistribution of gold values. Initial differences in the quantity of gold separated from the mineralizing fluids at any point in a vein appear to vary in a general way with the width of the vein.

Although absolute values for a given width may not correspond throughout the mines, within certain geographical limits it is found that narrower stringers are of lower grade than the wider sections of the veins. Intermediate vein widths carry proportional gold values.

The approximate rule of the increase in gold values with the width appears to be true only up to a certain point. The optimum width, at which the values are highest, varies throughout different sections of the mine. For widths greater than the optimum width, and including naturally many of the fold sections, the values begin to be highly erratic and the effect of late redistribution outweighs those factors connected with the initial separation of the gold from the mineralizing fluids.

A typical set of average assay values, computed by taking a large number of determinations for each width in a certain section of the Mysore mine, is shown below:

Width, *inches*	Number of cases averaged	Average assay, *ounces*
3	25	0.24
6	41	0.49
9	45	0.65
12	56	0.75
15	63	1.10
18	50	0.99
21	15	0.78
24	11	0.42

These figures were from a section of low average width so that few determinations were made for widths of vein material greater than two feet. The steady sequence of values was better shown than in any other set of assay averages.

Another section of the same mine showed the following results:

Width, *inches*	Number of cases included	Average assay, *ounces*
6	13	0.82
9	12	1.07
12	13	0.82
15	21	0.96
18	31	0.74
21	16	0.59
24	36	1.18
27	16	0.97
30	42	1.02
36	26	1.22
42	22	1.83
45	15	1.61
48	11	1.03

That the probable approximate relationship of values to width is no peculiar coincidence connected with the Kolar gold field is indicated by the following suite of averages from a portion of the H vein at the Sigma mine in Quebec, Canada #:

Width, *inches*	Number of cases included	Average assay, *ounces*
24	51	0.12
30	66	0.14
33	31	0.21
36	50	0.21
48	70	0.31
60	89	0.41
64	35	0.29
72	98	0.29

In summary, the localization of gold values may be attributable to a combination of two variable factors: first, differences in the amount of gold released from solution during the initial period of separation, whether in the crystalline or fluid state; secondly, the redistribution of values through the influence of local stress conditions on previously separated gold that has retained a state of mobile fluidity.

A statistical analysis of comparative assay figures for the sections of the veins respectively adjacent to the hanging-wall and foot-wall in different parts of the Mysore mine makes it possible to generalize upon the disposition of the gold within the fissures:

(1) in flat-dipping sections of the veins there has been a concentration of gold values towards the foot-wall; 68 per cent of the cases studied followed this rule and the degree of concentration was 77 per cent.

(2) in a steeply-dipping vein the values appear to be concentrated towards the hanging-wall in 76 per cent of the cases; the degree of concentration was 78 per cent.

(3) along the *nose* of *folds* 83 per cent of the cases show concentration towards the hanging-wall to the extent of 74 per cent of the total gold content.

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(4) along the *trough* of *folds* 80 per cent of the cases show a 73 per cent degree of concentration towards the foot-wall.

The foregoing results would seem to show that there has been a degree of gravity concentration of the newly separated fractions high in metallics during the initial stages of mineralization.

Where the lode is of steep dip, the velocity of the solutions and its effect upon freshly released residuals appears to have outweighed the effect of gravity. The gold-rich fractions are carried towards the hanging-wall by the stream flow.

Similar conclusions appear valid in the case of *folds*. Here the tendency is accentuated (i) by the centrifugal effect of the velocity of the solutions around the *outside* of a curve in the channel, and (ii) through the influence of factors connected with the late redistribution of values in response to stressing of the folded structures.

The migratory phenomena suspected appear to represent a valid tendency rather than an infallible rule. The expected results are frequently modified by irregularities in the vein walls, the effect of branching fissures, and the character of the parting undergone by the highly fissile material of the zones of shear. Each of these circumstances would produce eddies and conflicting currents within the stream, and tend to produce a divergence in the results from the calculated effect.

Inevitable departures from a strict control by the underlying principles of initial separation may be brought about by purely local irregularities. Late redistribution of values is affected strongly by differential competency in the vein filling and its adjacent wall-rock material.

The fineness of the bullion produced from the Kolar veins shows a tendency to increase with greater depth, according to Pryor's estimate (23). This may be explained in the following terms: the critical pressures for the separation of gold and silver from the mineralizing fluids may be assumed to be P_g and P_s respectively. If the local pressure drops to P_1, becoming less than the critical pressure of either metal, then deposition or separation of both gold and silver will occur. The rate of separation will be proportional to some function of the difference between the local pressure and the critical pressure for either metal. Thus the rate of separation for gold will be proportional to some function of $(P_g - P_1)$ and for silver it will vary as a function of $(P_s - P_1)$. The ratio of gold to silver after a given time will be:

$$\frac{\text{constant} \times f(P_g - P_1)}{f(P_s - P_1)}.$$

The average ratio for a given temperature horizon will depend upon the average pressure.

If it be assumed that P_g is greater than P_s, as would appear likely by analogy with the other physical constants of the two metals, then the ratio of gold to silver will be less for a greater reduction of pressure, *i.e.* at a higher elevation within the crust. Thus the fineness will decrease at shallower depths, or will increase at greater depth.

As a numerical example, if the relationships vary in direct proportion to the pressure differences, and the constant in the equation be assumed as unity: take P_g as 500 units, and P_s as 400 units, for a local pressure equivalent to 200 units the ratio of gold to silver separated and deposited will be $(500 - 200) : (400 - 200)$ or $3:2$; and for a local pressure equal to 100 units the ratio would be $(500 - 100) : (400 - 100)$ or $4:3$. Thus the ratio of gold to silver is less for the lower local pressure, *i.e.* for the shallower horizons within the earth's crust.

It may be considered that the fundamental ratio shown by Pryor's statistics is borne out by theoretical indications. When depths are reached at which the local pressure everywhere exceeds P_s, then it may be expected that the silver present in the bullion will become negligible.

When the local average pressure approaches P_g, then it will have been impossible for either gold or silver to become separated and barren quartz grading to pegmatite may be expected. The dynamic stage of separation of gold values during the period when the solutions are in motion will be barren, but small amounts of residual solution remaining fluid after movement ceases may contain gold and silver up to the point of saturation in the solution. These may be trapped in the final stage of crystallization and produce isolated pockets showing values.

There is no indication that the barren quartz horizons will be reached at any depth to which mining operations are presently possible.

An attempt has been made to explain the apparent relationship of the gold : silver ratio. Through an application of Bernouilli's theorem it would be theoretically possible to calculate the anticipated grade of vein material for any given width, provided that all other constants were known. In the existing state of knowledge it is possible to do not more than suggest that points of pressure release encourage the separation of metallic values in their vicinity and this has been emphasized in a previous contribution (43).

The difficulties brought about by indeterminate local irregularities of vein structure, as well as by complexities in the geologic history of the mineralization of any given section of a vein, and the impossibility at present of obtaining a sufficient and proper amount of data, have so far vitiated attempts to evolve an approximate formula connecting the grade of a vein with the width in direct fashion for a given horizon of deposition.

Repeated reopening of the Kolar veins has not occurred, as it has done at many other places and resulted in several ages of introduction of gold. Thus this field would appear to offer possibilities for fruitful investigations that are not presented elsewhere. The mineralization of the Kolar veins has been confined to a single period. Some refracturing of the narrower sections of the veins has occurred during this one period and movements along the transverse thrusts have been repeated throughout the process.

The period of mineralization may be divided into the dynamic stage of separation of metallic values from moving solutions and the static stage of final crystallization after the fluids came to rest.

Mobile fluidity of certain residual fractions may be inferred through to the stage at which most of the quartz had crystallized. Differential pressures

upon sections of the lodes at various times in the history of the mineralization process probably permitted the migration of fractions within which the gold became concentrated. The residual fractions might move through the vein system several times as the loci of zones of compression and of tensional dilation were changed in response to varied environmental pressures. This concept demands further study and elucidation.

APPLICATION OF KNOWLEDGE IN THE GUIDANCE OF DEVELOPMENT POLICY.

The period of study of the Champion lode engaged in by the author covered the period between February 1937 and August 1938. Subsequent development policy at the mine showed the strong reinforcement of development at depth by upper-level probing with highly valuable results.

Data for the expansion of development in many of the old abandoned levels was provided in the form of a longitudinal section through the mine workings, and covering report. Fig. 12 is a condensed and simplified version of this section and the original showed every known fold along the vein structures and traced each one through from surface to the lowest levels of the mine.

Many obvious gaps in the routine development of the lode were thereby brought to light in the projection of the major folds up and down the line of pitch from places where they were already well exposed underground.

Additional development necessary to explore the existing gaps in the ore-bearing structures was outlined in a program that would have taken ten years to fulfil at normal rates of development.

The majority of the points designated for more immediate investigation on those levels of the mine above the 76th were located on or near, or were calculated soon to approach one or other of the major fold structures.

Development of ore in the upper levels, limited only by war-time cutbacks in exploratory expenditures, may be illustrated by reference to the results in the two succeeding years, taken from the published reports of the Mysore operation:

1939 ..... 2,304 feet of 1.23 ounces over 30 inches
1940 ..... 1,493 feet of 1.30 ounces over 20 inches

The correlation of all possible geological evidence, obtained by a competent staff trained in the modern techniques of underground mapping and the recording of the maximum amount of data from the core provided through diamond drilling, would be productive of considerable economies in the development of the remaining ore bodies to be found from surface to depths of 10,000 to 12,000 feet below the collars of the shafts.

Work of a detailed geological nature has hitherto only been accorded a secondary importance. This has been due in part to the lack of initiation of any intensive study by men thoroughly skilled in this phase of the science of mining, inhibited in its turn by the obvious nature of much of the ore mined to date.

Thousands of pounds that otherwise might be spent in abortive development can be saved by the adequate exploitation of current advances in geological technique as they become available.

The use of the diamond drill in an intelligent manner would be of the utmost value in promoting the more efficient development of these mines at certain horizons. The objection has been raised that diamond drill data are frequently not in complete agreement with the results of underground work. Where the quartz widths and assays are the only data given consideration this may sometimes be true, but the main usefulness of the information to be derived from drilling lies in the predictions that can usefully be made concerning structural conditions in little-known blocks of the property. It is common knowledge that assay values, in particular, that may be obtained from drill cores, are often no true measure of the ore potential even of small areas of a vein; nevertheless the intensive application of diamond drill control carried out by Canadian mines is indisputable evidence of the indispensable nature of the technique.

The usefulness of the diamond drill in the Kolar mines is limited only by the physical state of the wall-rocks in the vicinity of the workings. As greater depth is attained, the advantages of replacing the oxygen-consuming laborers employed in driving exploratory crosscuts and headings by machines liberating cool air must suggest themselves.

In conclusion it may be stated that there is now sufficient evidence available from the underground workings of the Kolar gold field to show conclusively *why ore is where it is*. The technicians should now be able to make a close appraisal of the probable extent of the barren sections of the veins, as well as those of mining worth.

As with other and similar operations throughout the world, the Kolar mines stand to derive considerable benefit from the employment of one or more pre-Cambrian geologists on the staff of each operation. Their efforts should be coordinated by some one competent individual conversant with conditions throughout the extent of these remarkable deposits.

CONCLUSION.

There yet remains to be written and compiled a comprehensive record of the geology of the Kolar gold-quartz veins and their setting. This situation is much to be deplored in the fact that it has not been remedied during the course of a highly profitable lifetime of the mines, attaining a span of more than sixty years.

A composite work by a team of specialists, and comparable with the many fine memoirs published by the United States and the Canadian Geological Surveys on individual mining districts, would not alone enrich the literature of economic and pure geology, as well as increasing the sum total of geological knowledge, but would prove of inestimable value as a guide to the efforts directed towards prolonging the economic life of the mines.

It is hoped that the present paper will serve to focus attention and interest upon one of the more unique and important gold occurrences of the world. An attempt has been made to provide a necessarily brief summary of those features considered to be of greatest economic significance. Many of the associated phenomena require further elucidation that can only come from the combined studies of a number of men.

The Kolar gold field of Mysore State is outstanding among those best adapted to a study of the hypothermal quartz veins and the factors influencing their local characteristics of economic and scientific interest.

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January 14, 1947.

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THE PHOSPHATE DEPOSITS OF THE EASTERN PROVINCE, UGANDA.

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ABSTRACT.

Large phosphate deposits occur along the southeastern border of Uganda which are similar in their ring shape and associations with soda and lime rich rocks to complexes described in many other parts of the world. A few interesting new features however have been observed in this area.

INTRODUCTION.

IGNEOUS activity which has produced plutonic, hypabyssal and volcanic rocks rich in soda and calcium is evident in many centres along a belt running from Kenya [1] along the eastern side of Uganda well into the Southern Sudan.[2] In Uganda the activity is seen in many mountain and hill features from Elgon in the extreme south to the Zulia-Lotukei complex which strides the Sudan-Uganda border. Most prominent in size and most diversified in rock type are the major volcanoes, which are of two ages, namely, Late-Tertiary and Pre-Tertiary. The first named are represented by high mountains which were originally cones subjected to a varying degree of dissection; they include, from south to north, Elgon (14,178 ft.), Kadam (10,050 ft.), Napak (8,300 ft.), Moroto (10,000 ft.) and Toror (6,496 ft.); several smaller centres of this age are also to be found. Descriptions of Napak [3, 4] and Elgon [5] have been undertaken by members of the Survey and reconnaissances have been made of others.

The earlier group of volcanoes cannot be dated with anything like precision and must be assumed from their denudation to be post-Karroo and pre-Tertiary. They all occur within 20 miles of the southwestern foot of Mount Elgon and are now generally marked by a carbonatite core which stands above the level of the great plain which stretches out to the west. Five centres have been recognized, namely, Sukulu, Tororo, Bukusu, Sekululo and one which is at present entirely covered by the rocks from Elgon and whose presence is inferred from evidence given by the basal rocks of the newer volcano. It is by no means certain also that this is the only hidden eruptive centre of this age.

The pediments that surround the carbonatite cores are underlain by roughly concentric bands of rocks which show a similarity of type to position that is common to all the volcanoes. In addition certain of the bands around Bukusu

[1] Pulfrey, W., Geol. Mag., LXXXI: 191–192, 1944.
[2] Verbal information from G. W. Grabham.
[3] King, B. C., An. Rept., Geol. Surv., Uganda, pp. 26 and 27, 1939.
[4] King, B. C., Memoir No. V, Geol. Surv., Uganda. *In Press.*
[5] See also Odman, O., Geol. Fören. i Stockholm, Förth. Bud. 52, H. 4, pp. 455–537, 1930.

and Sekululo form fairly prominent arcuate ridges which rise to 100 feet or more. Unfortunately the pediment, which forms part of the late Tertiary peneplain, is everywhere covered with a hard crust variously called laterite, duricrust and ferricrete. In Uganda this is a cellular and concretionary material which only rarely gives an indication of the rock type which lies below. The duricrust of this peneplain averages some 11 feet in thickness and can often be penetrated economically only by blasting. The rock itself below this cover is heavily weathered, a feature which may be found to a depth of 145 feet or more. These complexes (including small patches of Elgon tuffs overlying the carbonatites of Sekululo and Bukusu) occupy a combined area of some 36 square miles but only around the carbonatite at Tororo however and in very restricted localities around Bukusu and Sekululo do even weathered rocks outcrop.

All four volcanoes are set in granite, and, broadly speaking, are associated with five roughly concentric belts which, reading from the granite inwards, are as follows: (*a*) granites with sodic hornblende. (*b*) Kalisyenites, pulaskites, fenites [6] and their melanocratic counterparts. (*c*) Mixed rocks with a preponderating amount of ijolite but including nepheline-syenite (of foyaite type), melteigites, urtites, pyroxenites, biotite-pyroxenites, dunites and rocks showing every mixture of biotite, kataphorite and diopside. Wehrlite is also very probably present. (*d*) A magnetite-apatite-phlogopite band with insignificant amounts of silicates. (*e*) Carbonatites, which are mainly fairly pure limestone with widespread magnetite, apatite and phlogopite and often pyroxene, pyrite and haematite and fluor. At the outer edge of the limestone, garnet, wollastonite, tremolite, koppite, anatase and other minerals occur; over short distances too, rocks comparable with sövite and ringite of Brögger's descriptions are to be found, especially at Tororo. Manganiferous minerals are common at Sukulu, but the magnesium content of the limestones is low and only occasionally has siderite been noted, though there is often staining with iron.

This succession shows overlapping and omission in many places and intimate mixture takes place at such junctions as have been observed, *e.g.*, on Tororo hill rocks of the fenite type are inextricably mixed with limestones. A pipe-like mass of agglomerate surrounded by syenite occurs on the S.W. side of the Tororo carbonatite and one small patch of agglomerate has also been noted on the E. side of Sukulu.

It wil be seen therefore that the rock assemblages are similar to those described from many parts of the world and more particularly by Brogger,[7] Backlund,[8] Shand,[9] and several Russian authors. It would appear probable too that many of the occurrences hitherto described elsewhere also represent dissected volcanoes. The majority of the silicate rocks are equated in the lavas of Elgon and both silicate and non-silicate rocks of the plutonic types described

[6] Johanassen's nomenclature is used wherever applicable.

[7] Brögger, W. C., Die Eruptivgesteine des Kristianiagebietes, IV. Das Fengebiet in Telemark, Norwegen, 1921.

[8] Backlund, H. G., Bull. Geol. Inst. Upsala 24: 1–24, 1932.

[9] Shand, S. J., The granite-syenite-limestone comples of Palabora, E. Transvaal, Trans. Geol. Soc., S. Africa XXXIV, 81–105, 1932, *et. ap. al.*

in the earlier volcanoes are represented in the fragments of the Elgon agglomerates.

The pediments around Sukulu, Tororo and Bukusu where they are not cultivated are normally covered by fairly short grass and bushes which make inspection much easier than in many other parts of Uganda, but tall grass and dense bushes grow on the carbonatites. Sekululo, which is much nearer Elgon (Fig. 1.), is covered by dense cultivation everywhere.

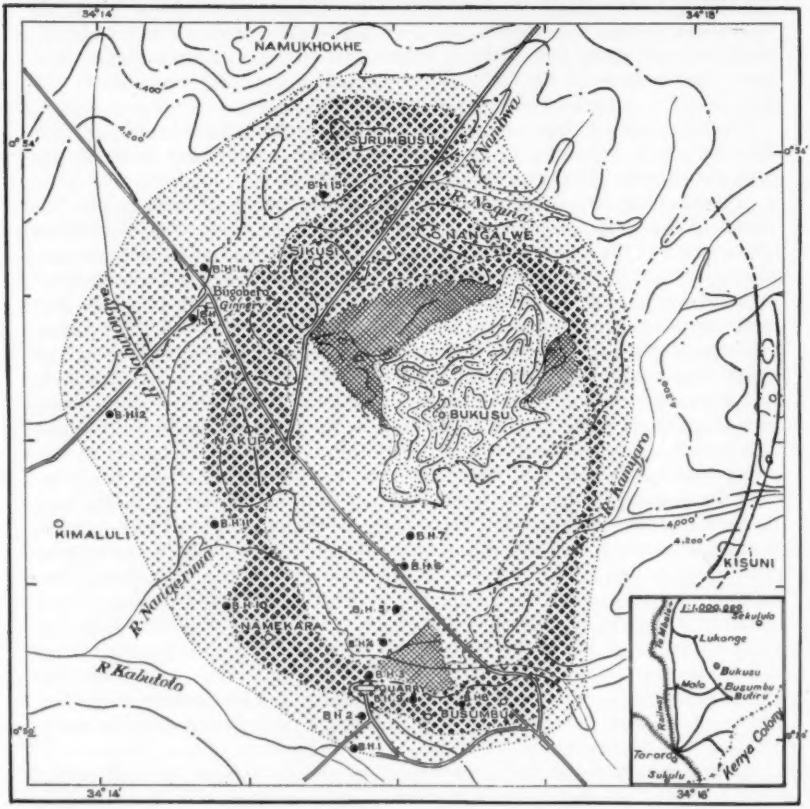
A description of these old volcanoes will be given in turn beginning with Bukusu, which possesses, so far as is known, the largest area underlain by magnetite-apatite-phlogopite rocks.

Bukusu (Fig. 1).—The area around this hill was examined by the writer between 1930 and 1932, but because of the ubiquitous duricrust no immediate appreciation of the underlying rock type was gained; the considerable amount of magnetite in the soil in certain localities, too, was thought to be connected with the limestone that outcropped at Bukusu Hill itself. Two pits some 600 yards apart were put down through the duricrust, however, in the region where the magnetite appeared plentifully. These pits reached rock at 14 feet, but the material was so fine-grained and heavily weathered that field determination was impossible; neither could petrographic examination be made until some time later, when it was seen that the rock in the pits contained about 20 per cent apatite. The petrological significance and economic possibilities of the area were then realized. No further investigations were undertaken, however, until the shortage of phosphatic fertilizers made itself felt in East Africa as the period of war lengthened. Prospecting by pitting was undertaken at the instigation of the East African Industrial Research Board, but as many pits even down to 60 feet only yielded a chocolate brown, earthy, material the writer detached a core drill belonging to the Water Supply section of the department to obtain information at depth. The cores obtained were 2½ inches in diameter, but owing to the depth and irregularity of the weathering coring was often impossible or undesirable and was undertaken only where the rock type changed. Jointing and fissures in the magnetite-apatite-phlogopite band caused loss of the mud in circulation through the drill and could be overcome only by cementing.

Closer inspection of the neighborhood revealed outcrops of high grade phosphate rock on Busumbu ridge some 3 miles anticlockwise along an arc from Nakupa where the first discovery was made, and large outcrops of magnetite were observed on Nangalwe at the opposite end of a diameter drawn from Busumbu. Inspection of the soil in other places is sufficient to give a clue to magnetite and phlogopite, but comparatively little is known of the true silicate rocks outside the specimens obtained in the boreholes. Of the 15 boreholes put down, 11 were in silicate rocks and 4 in the main phosphate band. The average depth of the boreholes was 126 feet including three of 70 feet in the phosphate rock.

The Form and Associations of the Deposits.—The magnetite-apatite-phlogopite band of rocks runs as a rough circle around the hill of Bukusu. This is a craggy ridge aligned NE.–SW., some two miles long and a mile wide, which rises some 1,300 feet above the surrounding country. It is covered for the

MAP SHOWING THE RING OCCURRENCES OF BUKUSU HILL. UGANDA



Scale

MILE 1 3/4 1/2 1/4 0 1 2 MILES

LEGEND

PRE-CAMBRIAN

GRANITES

POST-KARROO. PRE U-MIOCENE

SYENITES
NOLITES
PYROXENITES
ETC.,

MAGNETITE-APATITE-MICA ROCK

LIMESTONE (CARBONATITE)

U. MIOCENE

ELGON TUFFS AND AGGLOMERATES

BOREHOLES --- B.H.1

FAULTS

FIG. 1.

greater part by fine tuffs and agglomerates thrown out during the earlier phases of Elgon's activity and obviously laid on an irregular base of limestone (carbonatite) which had itself stood out above the region immediately around. The present visible extent of the carbonatite is small and occurs firstly at the base of two hillocks near the southwestern foot of the main hill and secondly in crags on the northeastern corner. An area of smaller extent underlain by limestone occurs on the left bank of the Kamijaro and at the base of the northern flank of Busumbu ridge. This appears from the drilling to be a subsidiary oval or circular mass possibly joined by a narrow neck to the main mass of carbonatite.

The junction between the carbonatite and the magnetite-apatite-phlogopite has been seen in one place only, namely, in a trench on the north side of Busumbu. Dikes of carbonatite have however been met with at depth cutting the outer rock formation.

Carbonatite also occurs as two small dike features at the southern end of the arcuate faults shown on the map 2½ miles east of Bukusu summit. These faults are obviously related to the intrusion of the neighboring complex, but cannot be traced farther south owing to lack of outcrops.

The magnetite-apatite-phlogopite belt forms a ridge for a distance of just over half a circle round the central limestone plug, on the western and southern side; generally this ridge is about 100 feet high and is broken across to form a series of gently rounded hills. On the south and east sides the band is normally between a quarter of and half a mile wide, but to the northwest, in the neighborhood of Surumbusu and Nangalwe, it widens to 1¾ miles. The magnetite-apatite-phlogopite rocks on the northern and eastern sides of Bukusu almost certainly narrow down considerably and are lost under the extensive riverine deposits of the Kamijaro and other streams.

The only known outcrops of phosphate rock occur on Busumbu ridge where considerable clearing of the bush has taken place since exploitation began. Here small platforms of grey to buff rock commonly mottled by crystals of magnetite are occasionally visible, and the outcrops tend to form a brow feature in the locality where the material is being quarried. The rock has also been exposed in recent work on the road cutting which crosses the eastern end of Busumbu ridge. It is obvious that the area would lend itself admirably to survey by magnetometer and it is possible with a dip circle to determine roughly the larger patches of magnetite.

Smaller bands of the rock of the same mineral assemblage may occur in the undersaturated rocks to the west and north of Nakupa and Busumbu, a point which is inferred from pits dug by the road which runs west. Veins possessing the same or similar minerals have also been met with in the boreholes (*e.g.*, No. 6).

Syenitic rocks, mostly of fine grain, occur commonly around the edge of the complex and have clearly been formed in situ from the granite in places where this is broken by faulting.

A dike feature that is younger than the magnetite-apatite-phlogopite band and runs for several miles near the NE.–SW. road is filled with a rock which, in the only locality where it is unweathered, has a pale grey, horny quality not

unlike that of an acid lava. It occasionally shows signs of brecciation and is crossed by tiny veins of quartz. The dike is exposed along the roadside at intervals for a mile or more north of the Nangirima, and it is presumed that a similar occurrence some 6 feet wide and having the same alignment and mineral composition which has been proved in trenches on Nakupa hill is an extension of the same feature. An analysis (W. H. Herdsman) is as follows: SiO_2—54.65%, Al_2O_3—6.83%, Fe_2O_3—.70%, FeO—.88%,MgO—.32%, CaO—15.40%, Na_2O—.15%, K_2O—2.48%, H_2O—105°, 1.30, H_2O—105°, 1.85%, TiO_2—.08%, MnO, CO_2 and S—nil, P_2O_5—13.50%, SO_3—1.75%, F, etc., N.D.

Syenite-porphyry, apparently of dike-like habit, is a feature of both ends of the occurrence.

It is possible that under the weathering conditions peculiar to this area bauxite occurs in certain localities.

Mineralogy of the Magnetite-Apatite-Phlogopite Band.—The proportions of the essential minerals of the bands, as already stated, vary widely from place to place, and considerable areas exist where one or other of the three minerals preponderate very markedly; in places where magnetite occurs exclusively it is lenticular in form. Fineness of grain, as is so common to deposits of this type elsewhere, is usual. This is especially true of the apatite and to a lesser degree of the mica flakes, which occur up to 3 inches across; the magnetite on the other hand has been found in crystals up to a foot in length. It would appear from the evidence gained from outcrops, prospecting pits and boreholes that the magnetite occurs in much greater amounts than the other two minerals, whilst it is also fairly certain that apatite is more common than the mica. The largest apparent development of magnetite occurs on Nangalwe Hill on the northwest side of Bukusu. This feature, which measures two-thirds of a mile in length and four hundred yards in breadth at the base and is some 160 feet high, is apparently composed of solid magnetite, and large blocks up to 6 feet or more cover the top and slopes. Chemical determinations on a bulk sample representing several tons of iron ore from Nangalwe showed .26% P_2O_5 and .13% S (Anal.: B. C. King).

The deepest borehole drilled into these deposits was 140 feet, but even at this depth weathering of the constituent minerals is intense. The magnetite is less attacked than the other minerals and its glittering surfaces often stand out against the normal brown and buff material formed by the weathering products of the other two, and stained by limonite. Phlogopite is never seen within at least sixty feet of the surface and is represented entirely by vermiculite. This is found in two forms, a bronze variety and a more flaccid, grey or biscuit type which breaks like damp cardboard. Tests on the material from one pit showed it to be only of fair quality for commercial purposes, but no attempts have been made to examine the vermiculite from the point of view of exploitation.

The rock, where phosphatic minerals form the major portion, is brown, friable and concretionary. The original mineral apatite gives place, to depths of at least 50 feet, to francolite-staffelite. Near the surface more than two-thirds of the original mineral has been replaced, but this alteration becomes

progressively less at depth; wherever weathering is evident, however, francolite occurs. The apatite is mostly limpid yellow, though white and fine-grained, green varieties also occur. Fine, dusty inclusions of iron ore are to be seen in many crystals as in those of the lavas of Mount Elgon; the crystals also sometimes contain small inclusions of silicates.

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Most of the rock within 50 feet of the surface is concretionary and composed of tiny, fully or partially formed spheres of francolite fused to one another and averaging one millimetre in diameter. These spherulites are composed of fibrous crystals of francolite (or staffelite as this fibrous form is usually called) which, under the microscope, show rhythmic, irregular, roughly circular bands which are clear and cloudy in turn. The core of the spherulite generally consists of a rounded crystal of apatite in varying stages of replacement; much less commonly the cores are fragments of magnetite or mica; occasionally there is no core. The refractive indices taken on six specimens are: Ne—1.611 and No—1.622. Much more rarely the rock is spongy and consists of a mass of interlocking, hexagonal basal plates which are similar to the original descriptions of francolite. Another feature of the concretionary material is the occurrence of occasional irregular layers up to half an inch thick of a cloudy, biscuit-colored material.

Analyses of the three phosphatic mineral types are as follows:

	Apatite (Busumbu)	Francolite (Busumbu)	Biscuit Colored Mineral (Busumbu)
CaO	47.60	55.35	55.15
MgO	.23	.14	.16
P_2O_5	35.52	39.55	39.42
F	1.96	3.79	3.96
CO_2	.43	1.80	1.95
Al_2O_3	.65	N.D.	N.D.
Fe_2O_3	6.05	.11	.10
H_2O—105°	.20	.30	.23
H_2O—105°–300° C	.35	.18	.10
H_2O—300° C	.85	.35	1.10
Insol. in conc. HCl	6.90	.05	.05
Less O for F	.82	1.60	1.67

(Anal.: Imperial Institute)

SO_3 was not detected [10] but about .1 per cent Cl was noted in each specimen. This is in agreement with tests made by the writer on earlier samples of apatite obtained from Nakupa.

It was impossible to obtain apatite free from impurities, which must include the alumina, iron, insoluble material and uncombined water of the tables. A recalculation therefore to 100 per cent in the analysis of the apatite gives the following figures:

CaO	54.97
MgO	.27
P_2O_5	41.02
CO_2	.50
F	2.26
Combined water	.98
Less O for F	.94

[10] Kennedy, W. Q., Summary of progress, Geol. Surv. Gt. Brit., Pt. II, pp. 53–59, 1935.

It will be seen from this that the mineral is a hydroxy-fluorapatite of comparatively low fluorine content.

At Nakupa Hill there is considerable redeposition of a fine, pearly apatite at depths below 25 feet; in other places clear cores of apatite are overlain with white apatite. On this hill and for two miles round the band in a clockwise direction the development of concretionary phosphate is not nearly so marked as in the region anti-clockwise from Nakupa to the main road.

Other minerals have been noted in association with the three main constituents, but even so they must be considered rarities. Diopside is the commonest, but perovskite, kataphorite and schorlomite also occur. Zeolites, of which natrolite and thomsonite have been recognized, together with quartz, occasionally cut across the phosphate rocks in tiny veinlets.

Exploitation.—About 5 million tons of ore carrying between 8 and 35 per cent phosphorus pentoxide are estimated, on the basis of close pitting and drill holes, to occur between the top of the Busumbu ridge and a plane 50 feet below and over an area some 2,000 yards long and 250 yards wide. Many times this amount must of course be represented in the deposits as a whole; this area is merely that which the pitting so far undertaken has proved to carry the highest grade of phosphate and the highest proportion of the citric soluble, carbonated phosphate. Equally good material of probably similar amount could be obtained by mining from the road two miles east of the present quarry. The rise between the road and the top of the hill is of the order of 200 feet.

Most of the magnetite-apatite-mica band however remains to be explored, though it would appear from superficial examination and pitting as far as the W. side as Sikusi that the deposits anticlockwise along the band from Busumbu are of consistently lower grade; separation of the phosphate fraction however should offer very little difficulty.

At present the material is being quarried at Busumbu to satisfy an East African demand for a thousand tons of phosphate a month. Curious as it may seem no use is at present being made of the high magnetic quality of the major part of the iron, and separation is achieved on the basis of the fact that the phosphate crushes to a much finer degree than the magnetite. Drying is undertaken, though mining by means of small adits secures an ore that is fine, powdery and possessing a very low moisture fraction. A final product which is less than 60 mesh (British Standard I.M.M.) is achieved by passing through a ball mill and trommel. This material contains a minimum of 20 per cent P_2O_5 and is used in that form as a fertilizer. It is patent that little if any of its citric solubility is derived from the apatite, but is due almost entirely to the francolite.

The intention is to place the working on a proper footing and to produce large quantities of phosphate of the "silicophosphate" type by fusion with another product of East African alkaline volcanic activity, the sodium carbonate derived from Lake Magadi in Kenya.

The quarry is only 8½ miles from a railway station but 700 from the seaboard; in the early stages of the working at least, production will be on the basis of sale to the East African market alone.

Tororo.—This is a mass of carbonatite running north and south, pear shaped in outline, and about a mile and a half in length. The northern and wider end rises in finger-like fashion some 700 feet above the plain and forms one of the most striking topographical features in Eastern Uganda. The zone of rocks between the granite and the carbonatite is probably rarely more than 400 yards in width, and syenite is found up the sides of the carbonatite cliffs. Nepheline rocks are rare and the belt of magnetite-apatite-mica seen at Bukusu has not been noted; a pipe-like mass of agglomerate however has recently been exposed in an excavation on the southwest corner and against the carbonatite. Patches of limestone with high apatite content are frequent on the northeast and on the western side, and if it were not for the large deposits available elsewhere search for phosphates here would be warranted.

Sekululo.—This is an old volcanic neck lying in the heart of the foothills at the western foot of Mount Elgon. Its character was first suspected by the occurrence over a circular area of fine needles of sodic hornblende in the granite, which also showed arcuate crush zones on the eastern side. The neck, which must measure some three miles across the undersaturated rock complex, is probably circular in outline, but is covered almost completely by tuffs thrown out in the earlier phases of Elgon's activity, which are piled high into a rounded hill 3 miles across and 1,800 feet above the base. Closer examination showed that rocks of nephelinitic, pyroxenic and micaceous types occur in an arcuate ridge 100 feet high about two miles long on the southeast side of the main hill. This ridge is broken up into a series of individual hills which, like the country around, are covered with dense cultivation. The extremely deep soil offers little hope of outcrops on the ridge, and the only one seen is of very weathered rock. Along the outer side of the ridge, and in fact marking what must be the outer margin of the complex where it is not covered by tuffs, are riverine deposits.

Several samples of weathered rock, however, have been obtained from the southwestern foot of the main hill which have yielded over 20 per cent phosphorus pentoxide.

Sukulu.—The carbonatite of the Sukulu complex is the largest of all these occurences and measures 2½ miles across. It is almost circular in outline and carries a wide variety of minerals on its outer edge. Extremely hard duricrust blankets the pediment for at least a mile away from the carbonatite cliffs on all sides of the perimeter. In view, however, of the suitability of the area for the working of phosphate deposits should they occur, two lines of boreholes were put down one on the eastern side and one on the southwestern side. The first named series of holes showed that the band of rocks lying within the granite and between it and the carbonatite must be 400 yards or less in width.

On the southwestern side, where the circular group of hills which form Sukulu show a funnel shaped opening, the drilling has indicated that the magnetite-apatite-mica band is about 500 yards wide and must thus form a big bulge in this region even if it does not extend to this width on the western side of the hills. High percentages of apatite occur down to the limit of the holes (160 feet), though it would appear that magnetite is at least as common as apatite. Mica is again not prominent at this point. The deposits are heavily

iron-stained and friable throughout the depth stated, but no development of francolite has been noted.

Origin of the Deposits.—The association of deposits of this type with the carbonatite-soda rich complexes has been well documented; a similar relation exists between the huge magnetite deposits of Northern Sweden and elsewhere and syenites.

The general relationship might be of the following type:

$$Na\ Fe\ Si_2O_6 + FeSiO_3 + Fe_2O_3 = Na\ Al\ Si_3O_8 + Fe_3O_4.$$

In other words syenite plus magnetite could be produced from a magma that under other conditions might solidify as pyroxene. Thus syenite would be formed apart from that which is represented by ore replacement in situ of the granite around the perimeter of the complex. In the Bukusu complex the commonest rocks are syenites, ijolites, biotite-pyroxenites and pyroxenite; it should be pointed out however that the biotite usually bears a transgressive relationship to the pyroxene.

Pyroxenites too are common at certain horizons as inclusions in the Elgon agglomerates. The relationship of biotite-pyroxenites on the other hand to the potash-rich volcanics of the Bufumbira area of Western Uganda has been given much attention by Holmes.[11] Amongst other things he has pointed out the frequent association of large quantities of apatite with biotite-pyroxenite.

Although the pyroxene at Bukusu is at least largely diopside, the presence of sodic material is indicated by the replacement of the diopside in most places by kataphorite. The disposition of the minerals at Bukusu is similar to that in pegmatitic bodies and the Uganda occurence can only be judged in that light. The occurrence of small veins of similar material elsewhere and the transgressive nature of veins of each of the three minerals concerned also points in the same direction.

It is the opinion of the writer therefore that the magnetite-apatite-mica represents a deuteric stage [12] product of an ultra-basic magma which contained a large quantity of fugitive hyperfusible material; generally speaking rocks of this mineral association were injected subsequently to the undersaturated silicate complex and before the lower temperature carbonatite. It is possible that a rock of the wehrlite type with hyperfusibles, alkalies and alumina gave rise, without addition, to the band described as well as to some of the syenites. It is clear that with the persistence over a long period of time of a widespread magma basis of unchanging type, similar rock and mineral associations may be expected to occur under the agglomerates of the newer volcanoes as shown by King in the case of Napak.

It is hoped when fuller examination of these rocks has been made that further clues to their origin will be forthcoming.

Geological Survey,
Entable, Uganda,
Dec. 6, 1946.

[11] Holmes, A., Mem. No. III, Pt. II, Geol. Surv., Uganda, pp. 19–59.
[12] Shand, S. J., Journ. Geol. LII: No. 5, 342–350, 1944.

STUDIES OF MINERAL SULPHO-SALTS: XI—WITTICHENITE (KLAPROTHITE).[1]

E. W. NUFFIELD.

ABSTRACT.

Part of a distinct crystal of wittichenite from Schapbachthal, Baden, showed the forms $c(001)$, $w(011)$, $y(031)$ new, $h(102)$, $i(203)$ new, with reference to the orthorhombic axial ratios:

$$a:b:c = 0.7430:1:0.6489$$

given by the unit cell which has the symmetry of the space group D_{2h}^{24}—$P2_12_12_1$ and the dimensions $a = 7.66$, $b = 10.31$, $c = 6.69$ kX. With $2[3Cu_2S \cdot Bi_2S_3]$ in the unit cell the calculated density is 6.19 as compared to 6.01 measured on this material, 6.2 calculated from the reflectivity, and 6.19 measured on artificial $3Cu_2S \cdot Bi_2S_3$.

The compound $3Cu_2S \cdot Bi_2S_3$ (wittichenite) was easily made by dry fusion, but not $3Cu_2S \cdot 2Bi_2S_3$ (supposed klaprothite). In addition the compound $3Cu_2S \cdot 5Bi_2S_3$ was obtained in well developed monoclinic blades, elongated with $b[010]$; these have space group $C2/m$ and $a = 13.08$, $b = 4.00$, $c = 14.70$ kX, $\beta = 99°24\frac{1}{2}'$, $Z = 1$; G (calculated) 6.63, (measured) 6.62.

Detailed study of numerous specimens of so-called klaprothite from the type locality and other occurrences revealed only wittichenite and emplectite and other known minerals.

WITTICHENITE.

In the new Dana (3) klaprothite has the appearance of a well defined mineral species, with orthorhombic elements and fourteen crystal forms recently determined by Wolfe, and the accepted composition, $3Cu_2S \cdot 2Bi_2S_3$, seemingly well supported by four analyses. The synoptic description of the mineral is complete, except for the cell dimensions and space-group of the structure, and the present work had the originally limited objective of supplying these missing data. For this purpose Professor Charles Palache and Dr. C. W. Wolfe very kindly placed their entire material at our disposal. This consisted of two specimens of copper-bismuth ore in barite gangue, from Schapbachthal, Baden (Harvard Mineralogical Museum, 82408, 82409); a single crystal with goniometric observations by Wolfe; three x-ray powder photographs, including one which had provided the data for klaprothite in Harcourt's Tables (6); and unpublished notes on polished sections by Larsen III. Other fine specimens of copper-bismuth ores were lent by Dr. E. P. Henderson of the United States National Museum, Professor V. B. Meen of the Royal Ontario Museum of Geology and Mineralogy, and Dr. R. J. Holmes, Columbia University. Professor M. A. Peacock generously gave the benefit of his experience both during the study of this material and the preparation of the manuscript.

[1] For recent parts of this series see Nuffield (12); Peacock and Berry (13) (numbers in parentheses refer to Bibliography at end of paper).

CRYSTALLOGRAPHY.

Wolfe's single crystal of klaprothite was too large for x-ray measurements, but eventually a suitable equidimensional crystal fragment was detached from the Harvard specimen 82409. This crystal was light lead-gray with a bluish iridescent tarnish and a conchoidal fracture but no cleavage, and it showed parts of two zones with mutually perpendicular axes, giving a habit recalling that of bournonite. In Wolfe's notation for klaprothite the forms observed on this crystal are $c(001)$ the broadest face, $h(102)$ broad, $w(011)$ narrow, and two new forms, $i(203)$ and $y(031)$, both as narrow faces. The angles measured on these faces compare as follows with the angles calculated by Wolfe from his geometrical data and by the present author from the subsequently determined cell dimensions:

	Measured	Calculated	
	E.W.N.	Wolfe	E.W.N.
$c(001) : w(011)$	33°06′	32°44′	32°59′
: *$y(031)$	63 47	62 35½	62 48½
: $h(102)$	23 30	23 25½	23 35½
: *$i(203)$	30 01	30 00½	30 12½

The identity of the x-ray crystal with Wolfe's klaprothite was confirmed by the identical x-ray powder patterns that were obtained from a part of the x-ray crystal (Fig. 1) and a part of Wolfe's crystal (Fig. 2).

The crystal thus positively identified with Wolfe's klaprothite was rotated about $b[010]$ and $a[100]$. The rotation photograph and the Weissenberg resolutions of the zero and first layer-lines, with [010] as the rotation axis, showed orthorhombic symmetry and gave:

$$a = 7.66,\ b = 10.31,\ c = 6.69\ \mathbf{kX}$$

A Weissenberg resolution of the zero-layer with $a[100]$ as the rotation axis gave confirmatory values, $b = 10.32$, $c = 6.68$ kX. These cell dimensions give axial ratios which compare with Wolfe's geometrical ratios as follows:

$$a : b : c = 0.7430 : 1 : 0.6489 \quad \text{(E.W.N., } x\text{-ray)}$$
$$a : b : c = 0.7420 : 1 : 0.6429 \quad \text{(Wolfe, gon.)}$$

Projections of the single crystal photographs showed only the following systematically missing spectra: $(h00)$ present only with h even, $(0k0)$ present only with k even, $(00l)$ present only with l even. These conditions are characteristic of only one space-group, D_4^2—$P2_12_12_1$ (disphenoidal class 222).

With the specific gravity 6.01 measured by Frondel (3, p. 419) on the Harvard material from Schapbachthal, the empirical molecular weight of the unit cell is 1,926. Now the molecular weight of the accepted formula for klaprothite ($3Cu_2S \cdot 2Bi_2S_3$) is 1,506, which is incompatible with the molecular weight of the unit cell. This suggested that the material accepted as klaprothite might in fact be wittichenite for which the accepted formula is $3Cu_2S \cdot Bi_2S_3$. The molecular weight of $2[3Cu_2S \cdot Bi_2S_3]$ is 1,984, in fair agreement with the empirical molecular weight of the unit cell, and the density calculated for this cell content, namely 6.19, compares well with 6.2 calculated from reflectivity data on wittichenite by Phillips (16, p. 461), 6.1 calculated for arti-

ficial $3Cu_2S \cdot Bi_2S_3$ by Gaudin and Dicke (5), and 6.19 measured by the present author on artificial $3Cu_2S \cdot Bi_2S_3$. It seemed certain, then, that the new crystallographic data had been obtained on wittichenite rather than klaprothite.

TABLE I.

WITTICHENITE: $3Cu_2S \cdot Bi_2S_3$.

Orthorhombic, $P2_12_12_1$; $a = 7.66$, $b = 10.31$, $c = 6.69$ kX; $Z = 2$.

I	ϑ(Cu)	*d*(meas.)	(*hkl*)	*d*(calc.)	*I*	ϑ(Cu)	*d*(meas.)	(*hkl*)	*d*(calc.)
1	7.8	5.66 kX	(011)	5.612 kX				(141)	2.295 kX
1	8.5	5.20	(020)	5.155	½	19.75	2.28 kX	(320)	2.288
4	9.75	4.54	(111)	4.527				(132)	2.288
3	11.6	3.82	(200)	3.830				(222)	2.264
1	12.3	3.61	(121)	3.604	2	20.8	2.16	(013)	2.180
			(210)	3.590				(321)	2.165
1	13.35	3.33	(002)	3.345	½	21.5	2.10	(113)	2.096
			(201)	3.324				(330)	2.050
3	14.0	3.18	(012)	3.182	2	22.05	2.05	(023)	2.047
			(211)	3.164				(042)	2.042
			(220)	3.074				(241)	2.037
8	14.5	3.07	(102)	3.066				(312)	1.991
			(031)	3.057	2	22.8	1.984	(150)	1.991
1	15.1	2.95	(112)	2.938				(123)	1.977
10	15.7	2.84	(131)	2.839	½	23.8	1.905	(151)	1.908
½	15.9	2.81	(022)	2.806	3	24.0	1.890	(322)	1.889
4	16.85	2.65	(122)	2.635				(133)	1.817
2	17.4	2.57	(040)	2.578	3	25.05	1.816	(250)	1.816
			(230)	2.558				(340)	1.814
½	18.0	2.49	(310)	2.479	3	25.95	1.757	(052)	1.755
			(032)	2.397	2	26.4	1.729	(421)	1.734
3	18.8	2.39	(231)	2.389				(303)	1.680
			(301)	2.386	3	27.3	1.676	(160)	1.677
½	19.2	2.34	(311)	2.324				(430)	1.673
								(323)	1.597
					1	28.8	1.596	(252)	1.596
								(342)	1.595

I	ϑ(Cu)	*d*(meas.)	*I*	ϑ(Cu)	*d*(meas.)	*I*	ϑ(Cu)	*d*(meas.)
½	29.1	1.581 kX	1	38.8	1.227 kX	½	47.95	1.035 kX
½	30.0	1.537	½	39.8	1.201	1	49.1	1.017
1	30.8	1.501	½	40.1	1.193	1	51.05	0.988
1	32.05	1.449	½	40.6	1.181	½	51.95	0.976
½	32.3	1.439	½	40.95	1.173	1	53.25	0.959
1	33.2	1.404	1	41.7	1.156	1	55.75	0.930
1	33.9	1.378	½	42.9	1.129	½	70.5	0.816
1	36.6	1.289	½	45.0	1.087	½	71.15	0.812
1	37.3	1.269	1	45.7	1.074	½	77.35	0.788
1	37.9	1.251	½	46.65	1.057	½	79.9	0.781

To test this conclusion fusions corresponding to $3Cu_2S \cdot Bi_2S_3$ (wittichenite) and $3Cu_2S \cdot 2Bi_2S_3$ (klaprothite) were made with the powdered elements in evacuated silica glass tubes. In polished sections, the product with the composition of wittichenite proved to be a practically homogeneous coarse granular mass of anhedral crystals which gave a powder pattern (Fig. 4) identical with that of typical wittichenite (Fig. 3) and those of the natural crystal fragments (Figs. 1, 2). The product with the composition of klaprothite showed two

TABLE II.

"WITTICHENITE:" *X*-RAY POWDER SPECTRUM (HARCOURT).

I	*d*(meas.)	*I*	*d*(meas.)	*I*	*d*(meas.)	*I*	*d*(meas.)
(1) 9.0	3.12 Å	2.0	1.65 Å	1.0	1.16 Å	.3	.905 Å
.5	2.80	1.0	1.56	.3	1.105	.3	.890
(3) 2.0	2.32	1.0	1.44	.3	1.090	.3	.878
2.0	2.16	.5	1.36	.5	1.030	.3	.793
1.0	1.95	1.0	1.32	.5	.995	.3	.781
1.0	1.86	.5	1.27	.5	.965		
(2) 3.0	1.78	.5	1.21	.3	.928		

TABLE III.

EMPLECTITE: $Cu_2S \cdot Bi_2S_3$.

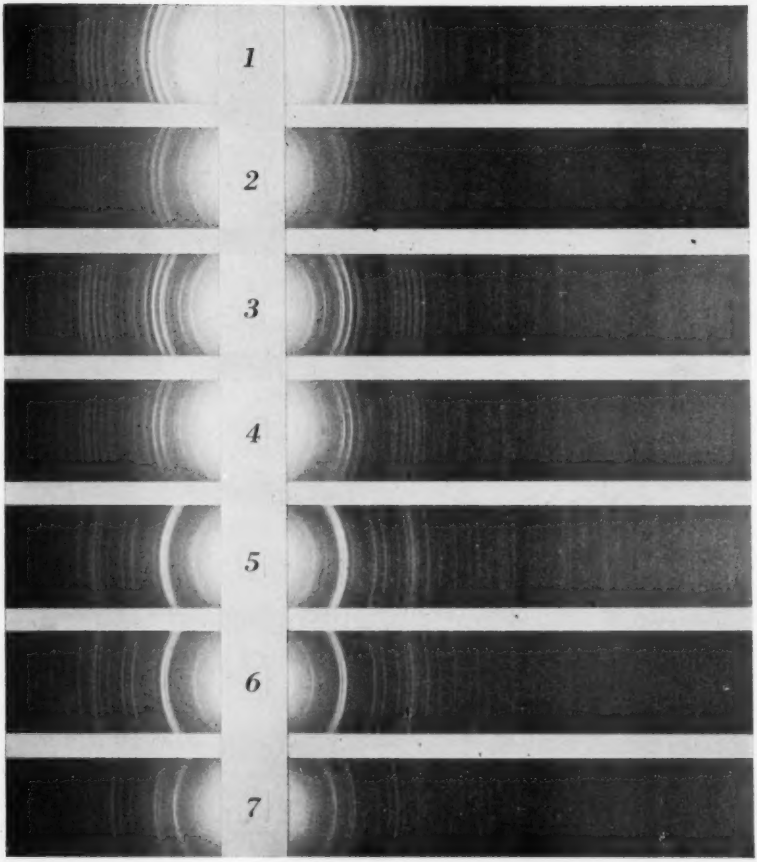
Orthorhombic, *Pnam*; $a = 6.125$, $b = 14.512$, $c = 3.890$ kX; $Z = 2$.

I	ϑ(Cu)	*d*(meas.)	(*hkl*)	*d*(calc.)	*I*	ϑ(Cu)	*d*(meas.)	(*hkl*)	*d*(calc.)
5	6.0	7.35 kX	(020)	7.256 kX	2	23.1	1.959 kX	(320)	1.965 kX
2	9.4	4.71	(120)	4.680				(170)	1.964
½	12.2	3.64	(040)	3.628	3	24.45	1.858	(251)	1.852
9	13.8	3.22	(111)	3.203	3	25.3	1.799	(122)	1.796
7	14.25	3.12	(140)	3.122				(311)	1.794
10	14.65	3.04	(031)	3.031	2	25.6	1.779	(340)	1.779
½	15.8	2.82	(220)	2.822	2	26.0	1.754	(321)	1.754
½	16.4	2.72	(131)	2.717				(171)	1.753
½	17.2	2.60	(230)	2.588	½	26.7	1.711	(042)	1.714
½	18.55	2.42	(060)	2.419				(261)	1.706
			(201)	2.406	3	27.7	1.654	(142)	1.651
5	19.2	2.34	(240)	2.340	½	28.5	1.611	(341)	1.618
1	20.0	2.25	(160)	2.250				(360)	1.560
4	20.85	2.16	(151)	2.175	2	29.6	1.556	(190)	1.559
			(231)	2.154				(232)	1.555

I	ϑ(Cu)	*d*(meas.)	*I*	ϑ(Cu)	*d*(meas.)	*I*	ϑ(Cu)	*d*(meas.)
½	29.95	1.540 kX	½	37.9	1.251kX	½	46.9	1.053 kX
½	31.5	1.471	1	38.95	1.223	½	47.75	1.039
2	32.05	1.449	1	39.6	1.206	1	49.3	1.014
1	34.3	1.364	1	40.3	1.189	1	50.3	0.999
½	35.35	1.329	1	41.3	1.165	½	51.8	0.978
1	35.75	1.316	½	43.8	1.111	½	52.4	0.970
½	36.7	1.286	½	44.5	1.097	½	54.1	0.949
½	37.3	1.269	½	44.95	1.088	½	56.9	0.918
½	37.5	1.263	½	45.8	1.072	½	57.9	0.907

phases in the polished section and gave a powder pattern unlike that of the crystals; this indicated that the compound $3Cu_2S \cdot 2Bi_2S_3$, if it exists, does not form under fusion conditions.

It thus became certain that the attempt to obtain the missing structural data for klaprothite had resulted in supplying this information for wittichenite, and that the geometrical crystallography and specific gravity given for klaprothite in Dana (3) actually apply to wittichenite. At the same time the existence of a distinct mineral klaprothite became doubtful; but before pursuing this question, the observations on wittichenite will be completed by the standard *x*-ray powder data and the usual microscopic information.



FIGS. 1–7. *X*-ray powder photographs with Cu-radiation (Ni-filter); camera radius $90/\pi$ mm. (1 mm. on film = 1° ϑ); full-size reproductions of contact prints.

FIG. 1. "Klaprotholite" (= wittichenite), Schapbachthal, Baden (HMM, 82409); part of *x*-ray crystal.

FIG. 2. "Klaprotholite" (= wittichenite), Schapbachthal, Baden (HMM, 82409); part of Wolfe's measured crystal.

FIG. 3. Wittichenite, Baden (ROM, M 12338).

FIG. 4. Wittichenite, artificial.

FIG. 5. Emplectite, Schapbachthal, Baden (HMM, 82409).

FIG. 6. Emplectite, Tannenbaum, Saxony (ROM, M 12328).

FIG. 7. $3Cu_2S \cdot 5Bi_2S_3$, artificial.

X-Ray Powder Pattern.—Wittichenite gives a distinctive powder pattern with numerous lines (Figs. 1 to 4). Table I presents the measurements and the calculated spacings for reflecting planes to ϑ (Cu) = 28.8° in the standard form used in Toronto. The Harvard x-ray powder photographs of "klaprothite" loaned by Professor Palache are identical with ours, and Harcourt's powder data for "klaprothite" (6; 2, card II–421), obtained from one of these, agree with ours except for the estimated relative intensities of the three strongest lines.

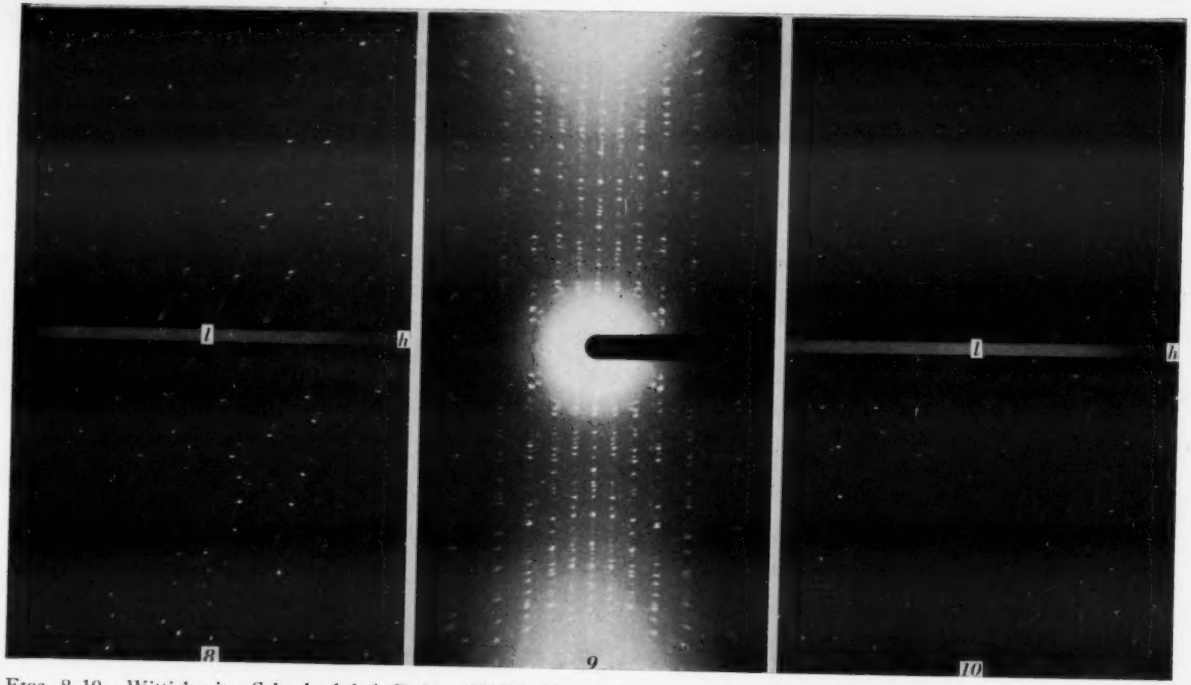
Harcourt (6, p. 103; 2, card II–1235) also gives intensities and spacings for wittichenite repeated here in Table II, but these were evidently obtained on emplectite ($Cu_2S \cdot Bi_2S_3$). When compared with powder data for emplectite from Saxony (ROM, M 12328) indexed on Hofmann's cell (Table III), it is seen that the two patterns are identical except that the triplet (d 3.22, 3.12, 3.04 kX) comprising the three strongest lines in emplectite (Fig. 6) is not resolved in Harcourt's pattern. Thus it is evident that Harcourt's "wittichenite" was emplectite, and Table I is submitted as a standard x-ray powder table to aid in the future identification of wittichenite.

TABLE IV.

WITTICHENITE: OBSERVATIONS ON POLISHED SECTIONS.

	Natural	Artificial
Etch reactions:		
1:1 HNO_3	Slow effervescence; some areas stain faint brown; fumes stain grayish brown, easily removed	No effervescence; negative; fumes quickly stain grayish-brown, easily removed
Conc. HNO_3	Effervescence; light brown stain, easily removed; fumes stain brown, easily removed	Slow effervescence; small areas stain iridescent blue, easily removed; fumes stain brown, easily removed
20% KCN	Bluish-iridescent stain, removed with difficulty	Faint violet stain, removed rather easily
1:1 HCl	Negative	Negative
Sat. $HgCl_2$	Negative	Negative
20% $FeCl_3$	Negative	Negative
Sat. KOH	Negative	Negative
Aqua regia	Slow effervescence; negative; fumes quickly stain brown to iridescent, easily removed	Effervescence; some areas stain iridescent, rub gray, removed with difficulty; fumes stain some areas brown, easily removed

Observations on Polished Sections.—Natural and artificial wittichenite, identified by powder photographs, was examined in polished sections. The mineral is coarse granular in texture, cream in color, and weakly anisotropic with polarization colors light to dark gray, tinged with brown in the artificial material. The etch reactions, summarized in Table IV, agree substantially with those obtained by Larsen III on the Harvard specimen 82409 and by Lindgren (10) on wittichenite from Colquijirca, Peru. Murdoch (11) and Davy and Farnham (4) on the other hand, obtained a light brown stain with KOH but observed no reaction with KCN. In this last respect these authors agree with Short (22) who obtained no reaction with KCN on one of Lindgren's specimens from Peru.



FIGS. 8–10. Wittichenite, Schapbachthal, Baden (HMM, 82409); single crystal *x*-ray photographs with Cu radiation, no filter; camera radius $90/\pi$ mm.; contact prints reduced to 2/3; rotation axis [010].

FIG. 8. Weissenberg resolution of the (*h*0*l*) layer.

FIG. 9. Rotation.

FIG. 10. Weissenberg resolution of the (*h*1*l*) layer.

"KLAPROTHITE."

The early mineralogists recognized only two ores of copper and bismuth, namely *Kupferwismutherz* (Selb, 1805, in 7, p. 1120) from Wittichen in Baden and *Kupferwismuthglanz* (Schneider, 1853, in 7, p. 997) from Saxony. On the basis of the original analysis, by Klaproth in 1807, Kobell proposed the composition $3Cu_2S \cdot Bi_2S_3$ for *Kupferwismutherz,* which he named *Wittichit* in 1830, improved to *Wittichenit* by Kenngott in 1853. This formula was confirmed by several analyses, notably those of Hilger and Petersen (7, p. 1121), while Schneider (20) prepared the compound in the wet way and proved its composition by an analysis agreeing closely with the formula. In regard to the crystal form of wittichenite nothing was recorded beyond a resemblance to bournonite, noted by Breithaupt in 1866. The composition of *Kupferwismuthglanz,* $Cu_2S \cdot Bi_2S_3$, was established by Schneider (1853, in 7, p. 999) and fully confirmed by later analyses, and the name *Emplektit* was given to the mineral by Kenngott, in the same year. The typical needle-like habit of the distinct crystals of emplectite, in contrast to the indistinct blocky appearance of wittichenite, was frequently noted and is significant in the present connection.

The name klaprothite (klaprotholite) arose from investigations of the copper bismuth ore from the Daniel Mine, Wittichen, Baden. According to Schneider (20) the ore occurred sparingly in reddish barite, mixed with much metallic bismuth. "Apart from some included chalcopyrite, it does not appear homogeneous: partly massive, fine grained, with weak lustre, in other places distinctly crystalline with strong metallic lustre; occasionally shows small prismatic crystal fragments in the barite. Their longitudinal striations, light gray color and very bright lustre recall the habit of bismuthinite" (20 *trans.*). Two analyses on samples containing some of these crystals gave the average composition:

Cu 28.82, Fe 0.91, Bi 51.40, S 18.69, total 99.82

This Schneider interpreted as representing a mixture of 76.30 per cent of wittichenite ($3Cu_2S \cdot Bi_2S_3$), 19.84 per cent of bismuthinite, and 3.68 per cent of native bismuth.

Petersen (14) and Sandberger (18) also examined specimens of the copper bismuth ore from the Daniel Mine, Wittichen, Baden. In this material they found no bismuthinite, but instead a mineral which differed from wittichenite in habit and color. This mineral occured sparingly with chalcopyrite and native bismuth in white barite, usually in long prismatic or needle-like crystals, but also massive. The crystals showed bright metallic lustre, steel gray to tin white color with yellowish tarnish, and excellent longitudinal cleavage. A single measurement of the prism angle gave about 107° and the specific gravity was estimated at about 4.6. The average of three analyses:

Cu 23.96, Fe 1.70, Bi 53.87, S 18.66, total 98.19

could be interpreted as a mixture of 86.91 per cent of a hypothetical new compound $3Cu_2S \cdot 2Bi_2S_3$, 5.73 per cent of native bismuth, and 5.55 per cent

of chalcopyrite. This supposed new compound was named *Klaprothit* by Petersen (14) and Sandberger (18); but it is interesting to note that Sandberger had previously considered the prismatic crystals in the Daniel ore as probably identical with emplectite, and in summarizing the properties of the newly named mineral he again emphasized its similarity to emplectite.

This, then, is the dubious origin of the species klaprothite, which resembled emplectite in habit, cleavage, color, and tarnish, but differed in prism angle (as indicated by a single measurement), specific gravity (which is obviously too low), and composition (founded on the recalculated average of analyses of very impure material).

MAY 7

Since material which had been accepted as typical klaprothite proved in the course of the present work to be typical wittichenite, some doubt regarding the very existence of the mineral called klaprothite naturally arose. From the numerous references that have been made in the literature to the mineral called klaprothite it seemed unlikely that this mineral has no separate existence. However it was clear that the question of the standing of klaprothite must be settled from a close study of representative material from the type locality; it would then be time to consider the significance of subsequent allusions to klaprothite. For this purpose several typical specimens of the distinctive copper-bismuth ores from various mines, including the Daniel Mine, at Wittichen, Baden, were obtained through the courtesy of the museum curators mentioned earlier. Each of these specimens was studied closely under the binocular microscope and every mineral in any way corresponding to the described characters of klaprothite, or those of any other bismuth mineral, was tested by *x*-ray powder photographs which were compared with the verified standard patterns. The result of this study is shown in the following tabulation which gives, first, the description on the label of each specimen and, second, the minerals found on the specimen.

"Klaprotholite," Wittichen, Baden (HMM, 82408) = wittichenite, native bismuth and tetrahedrite in barite.

"Klaprotholite," Schapbachthal, Baden (HMM, 82409) = wittichenite, emplectite, chalcopyrite and tetrahedrite in barite.

"Wittichenite," Neuglück mine, Baden (ROM, M 4073) = tetrahedrite in barite.

"Wittichenite," Wittichen, Baden (ROM, M 12338) = wittichenite altering to covellite and malachite, with native bismuth and quartz in barite.

"Klaprothite," Daniel mine, Baden (ROM, M 12344) = wittichenite altering to covellite and malachite, with emplectite and quartz in barite.

"Wittichenite," Wittichen, Baden (ROM, M 12997) = native bismuth and pyrite in barite.

"Klaprotholite and wittichenite," Daniel mine, Baden (USNM, 94137) = emplectite and wittichenite in barite.

"Wittichenite," Schlaggenwald, Bohemia (USNM, 85188) = bismuthinite in quartz.

"Klaprotholite and wittichenite," Daniel mine, Baden (USNM, C-738) = emplectite and wittichenite in barite.

"Wittichenite," Neuglück mine, Baden (USNM, C-770) = wittichenite in barite.

It will be noted that the five specimens labelled "klaprothite" or "klaprothite and wittichenite" were found to consist only of the known sulphbis-

muthites, wittichenite and emplectite, often accompanied by native bismuth and tetrahedrite as well as other known minerals; and when we recall the properties attributed to klaprothite it becomes increasingly clear that they refer either to wittichenite, or to emplectite, or a combination of the two. For example, the habit was described as acicular (like emplectite) or massive (like most wittichenite); the color, lustre, tarnish and cleavage were said to be exactly like those of emplectite; the roughly measured prism angle of 107° agrees nicely with the calc. angle $(110) : (\bar{1}10) = 106°51'$ for wittichenite; and finally the hypothetical composition of klaprothite, namely $3Cu_2S \cdot 2Bi_2S_3$, would be obtained from the analysis of a mixture of emplectite and wittichenite. In view of this correspondence of properties and the early authors' own recognition of the impurity of their material it appears certain that the supposed new species klaprothite was founded on a mixture of wittichenite and emplectite which are often intimately associated in the copper bismuth ores from the original locality.

During the present century the name klaprothite (or klaprotholite) has been repeatedly applied to a minor constituent in polished sections of copper sulphide ores. In view of the now apparent non-existence of a distinct mineral klaprothite at the original locality it will be interesting briefly to examine these later allusions to klaprothite and if possible to explain them in terms of the information gained in the present study.

Laney is frequently credited with the recognition of klaprothite in bornite-chalcocite ores, but the paper to which reference is often made (9), strangely contains no mention of klaprothite.

In connection with a study of the controversial intergrowths of bornite and chalcocite, Rogers (17) describes inclusions of a yellowish-white mineral, apparently the same as Laney's klaprothite, in copper ores from the Mountain Lake mine, 25 miles southeast of Salt Lake City, Butte, and several other localities; the few descriptive details given for this mineral are appropriate to wittichenite.

Murdoch (11, p. 38) examined a specimen of klaprothite from the original locality and decided that the validity of the species seemed doubtful. Schneiderhöhn and Ramdohr (21, p. 399) on the other hand consider Murdoch's decision as unjustified, but they state that the mineral is a great rarity, known only in the Wittichen deposits, and that the so-called klaprothite from Butte, with its lack of cleavage and its very slight reflection pleochroism, may be wittichenite. Under emplectite (p. 383) these authors summarize the properties of several bismuth ores, noting the similarity of emplectite and klaprothite in habit and cleavage and mentioning some optical differences.

Ahlfeld (1) reported wittichenite, klaprothite, and emplectite from the silver ores of Colquijirca, Peru, repeating the microscopic properties of these minerals as given by Schneiderhöhn and Ramdohr, but adding no significant observations.

Short (22) describes a specimen from Butte identified as klaprothite by Laney. The optical and etch properties given for this mineral by Short correspond with those of wittichenite, confirming the suggestion of Schneiderhöhn and Ramdohr.

Krieger (8), in a paper which has the appearance of placing klaprothite on a secure footing, describes pinkish creamy white, moderately anisotropic inclusions of this mineral in bornite from Concepcion del Oro, Zacatecas, Mexico. Dr. R. J. Holmes, Columbia University, was kind enough to send me two of the late Dr. Krieger's polished sections of this ore, clearly showing the blebs of the mineral in question. Two *x*-ray powder photographs on samples scraped from these blebs gave the typical pattern of wittichenife.

As we have shown, the additional crystallographic data given for klaprothite in Dana (3, p. 418) were actually obtained from wittichenite. Regarding the significance of the two Japanese analyses (nos. 3, 4 in Dana) we can say nothing definite since the original work by Harada is inaccessible; conceivably the samples analyzed were inhomogeneous like the original material from Wittichen.

Finally, the writer was informed by Dr. K. de P. Watson of the British Columbia Department of Mines that he had detected a mineral in high grade copper ore from the Rainy Hollow district, B. C., which gave etch reactions similar to those of Krieger's "klaprothite." Dr. Watson's suggestion that the mineral might be wittichenite was confirmed on one of his polished sections made in this laboratory by *x*-ray powder photographs, thus establishing a new occurrence for wittichenite.

These observations show beyond reasonable doubt that the mineral called klaprothite in copper sulphide ores is in fact wittichenite, and there is nothing in these later references to klaprothite which proves the existence of a mineral distinct from wittichenite and emplectite. Originally ill-defined and of doubtful identity, klaprothite appears to have been gradually promoted to the rank of an undisputed species, merely by the repetition of the name without the addition of any of the exact descriptive characters which are needed to define a mineral species.

ARTIFICIAL COPPER BISMUTH SULPHIDES.

Various artificially prepared copper bismuth sulphides have been reported in the literature and some have been prepared in the course of the present study. While the results obtained so far are incomplete they are of significance in connection with the question of the existence of klaprothite.

Phillips (15, 16) compared the density and reflectivity of the sulphide minerals with calculated values. For emplectite, klaprothite, and wittichenite, he gave the reflectivities 35, 34, 29.5, respectively, which suggests that his klaprothite was emplectite. He also noted that the originally reported density of klaprothite, 4.6, is much lower than the calculated value for the supposed composition, 6.4, and he stated that artificial klaprothite gave the density 6.3; but there is no evidence that this product was a homogenous compound with the composition $3Cu_2S \cdot 2Bi_2S_3$.

Schenck (19) reported the compounds $Cu_2S \cdot 3Bi_2S_3$, $3Cu_2S \cdot 5Bi_2S_3$, and $3Cu_2S \cdot 2Bi_2S_3$ in the Cu-Bi-S system, but the existence of these compounds was only indicated indirectly by the method used, and again there are no descriptions of the solid phases.

Gaudin and Dicke (5) prepared a number of compounds or mixtures of compounds by fusing various amounts of the elements Cu, Bi, and S in a crucible. They suggested that their phase A is either $Cu_2S \cdot 2Bi_2S_3$ or $CuS \cdot Bi_2S_3$ or perhaps $3Cu_2S \cdot 4Bi_2S_3$ (cuprobismutite—which has recently been discredited by Palache, in 3, p. 437); phase B was thought to be $3Cu_2S \cdot 2Bi_2S_3$ (klaprothite) or $3CuS \cdot Bi_2S_3$; phase C was believed to be $3Cu_2S \cdot Bi_2S_3$ (wittichenite) or $6CuS \cdot Bi_2S_3$. But the atomic ratios in these phases were admittedly uncertain and consequently the identifications of the compounds are doubtful.

The present attempts to prepare Cu-Bi-S compounds were made by placing weighed amounts of the powdered elements into silica glass tubes which were completely evacuated and sealed off. After fusion and cooling in air the product was broken, and part was mounted and polished for microscopic examination. If a homogeneous crystalline product was obtained the composition of the compound was that of the charge, and the *x*-ray powder photograph and measured density applied to that compound. If however two or more phases were present it was recognized that the compositions of these phases were not directly known, and *x*-ray powder photographs were made on samples scraped from single homogeneous area.

Charge $3Cu + Bi + 3S$: the product was practically homogeneous, and therefore its composition was $3Cu_2S \cdot Bi_2S_3$; closely resembled wittichenite in polished section and gave exactly the *x*-ray powder pattern for wittichenite (Fig. 4).

Charge $6Cu + 4Bi + 9S$: the product was an intergrowth of a phase X which occurred in well-developed blades together with a second phase which resembled wittichenite. The blades of phase X gave a distinctive *x*-ray powder pattern, while the pattern of the intergrowth was a combination of those of phase X and of wittichenite. As already stated this experiment showed that the compound corresponding to the supposed klaprothite ($3Cu_2S \cdot 2Bi_2S_3$) does not form under fusion conditions.

Charge $Cu + Bi + 2S$: the product was an intergrowth similar to the last but noticeably richer in phase X. This shows that emplectite ($Cu_2S \cdot Bi_2S_3$) is not obtained under fusion conditions and that phase X has a Bi:Cu ratio exceeding 1:1.

From a second fusion with the composition $Cu + Bi + 2S$, kindly prepared by Dr. F. G. Smith, it was possible to detach a single crystal of phase X on which the cell constants were determined by rotation and Weissenberg photographs. The direction of elongation proved to be the symmetry axis of a monoclinic lattice with space group $C2/m$ and dimensions $a = 13.08$, $b = 4.00$, $c = 14.70$ kX, $\beta = 99°24\frac{1}{2}'$. The specific gravity of several crystal groups gave four measurements, 6.58–6.65, average 6.62, and hence the molecular weight of the cell contents is 3045. The only simple rational formula which is richer in bismuth than $Cu_2S \cdot Bi_2S_3$ and is at the same time compatible with the known molecular weight is $3Cu_2S \cdot 5Bi_2S_3$ or $2[Cu_3Bi_5S_9]$ whose molecular weight is 3,049. The composition of the phase X is therefore provisionally taken as $3Cu_2S \cdot 5Bi_2S_3$, which is one of the compounds previously mentioned by Schenck and is probably also phase A of Gaudin and Dicke. This may

TABLE V.

$3Cu_2S \cdot 5Bi_2S_3$.

Monoclinic, $C2/m$; $a = 13.08$, $b = 4.00$, $c = 14.70$ kX, $\beta = 99°24\frac{1}{2}'$; $Z = 1$.

I	ϑ(Cu)	*d*(meas.)	(*hkl*)	*d*(calc.)	*I*	ϑ(Cu)	*d*(meas.)	(*hkl*)	*d*(calc.)
½	9.95°	4.45 kX	(202)	4.470 kX	½	18.0°	2.49 kX	(403)	2.501 kX
4	12.35	3.59	(203)	3.596				(205)	2.497
10	12.9	3.44	($\bar{1}$12)	3.450	½	19.05	2.36	($\bar{1}$15)	2.366
1	13.6	3.27	($\bar{4}$01)	3.263				($\bar{4}$05)	2.357
1	14.1	3.16	($\bar{4}$02)	3.144	2	20.0	2.25	(115)	2.258
½	14.65	3.04	(401)	3.044	½	20.75	2.17	($\bar{6}$01)	2.179
			($\bar{3}$11)	2.935				(510)	2.168
3	15.2	2.93	(113)	2.929				(511)	2.103
			(310)	2.929				($\bar{6}$03)	2.096
			($\bar{3}$12)	2.827	3	21.6	2.09	($\bar{1}$16)	2.089
8	15.85	2.82	($\bar{2}$05)	2.823				($\bar{5}$13)	2.089
			(311)	2.811				(601)	2.078
½	16.9	2.64	($\bar{3}$13)	2.638					
			($\bar{4}$04)	2.633					

I	ϑ(Cu)	*d*(meas.)	*I*	ϑ(Cu)	*d*(meas.)	*I*	ϑ(Cu)	*d*(meas.)
3	22.7°	1.992 kX	1	28.45°	1.614 kX	2	37.55°	1.261 kX
2	23.75	1.909	½	31.25	1.482	½	38.7	1.229
½	24.15	1.879	1	32.0	1.451	½	39.7	1.203
½	24.65	1.844	½	32.45	1.433	½	40.8	1.176
1	26.15	1.744	½	33.05	1.410	2	41.75	1.154
1	26.8	1.705	2	36.0	1.308	2	42.35	1.141
1	27.75	1.651	2	36.55	1.291			

correspond to the mineral dognacskite (3, p. 470), said to have the composition $Cu_2S \cdot 2Bi_2S_3$, specific gravity 6.79, and described as a gray, cleavable "wismuthkupfererz." Unfortunately, specimens were not available for study. In future work on natural copper bismuth sulphides the existence of this new compound should be borne in mind; it could be readily identified with the help of the data given in Table V obtained from the *x*-ray powder spectrum reproduced in Fig. 7.

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Jan. 14, 1947.

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SOME PHYSICAL CHARACTERISTICS OF CERTAIN FAVORABLE AND UNFAVORABLE ORE HORIZONS.

PART II.

OLAF N. ROVE.

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TESTS OF CRUSHING STRENGTH.

Introduction.—In preparation for the crushing strength tests a review was made of many past experimental studies and theories of rupture. An analysis of these theories lead to some apparently new ideas on the relationship between the surface of rupture, shearing and tensile strength, and the significance of these in terms of favorable ore horizons. To present these ideas it is essential to discuss in some detail the relationships between compressive, tensile, and shearing strengths, as well as the angle of shearing failure, Poisson's ratio, and other physical constants developed by earlier studies. Particular attention is given to an amplification and extension of Griggs' recent hypothesis.

Griggs (20, pp 557–564) found that under a confining pressure of 10,000 atmospheres (approximately equivalent to the static load at a depth of 35 km), the elastic limit (the strength at which strain lost its proportionality to stress, and then increased very rapidly until the ultimate strength was reached) increased only 10 per cent, while the ultimate strength might increase as much as 600 per cent. Griggs' data, indicating large deformation between the elastic limit and ultimate failure, imply deformation by rock

flowage; *i.e.*, twinning and slipping on glide planes, microscopic shearing; in nature, the recrystallization of a limestone would be expected under such conditions.

At the probable depths in the earth's crust that we are interested in, such extreme differences in the elastic and ultimate strengths would not be expected. Fig. 4 is a replotting and combining of Figs. 4 and 5 from Griggs' paper about which he comments (20, p 550), "The curves at low pressure (1, 2000, and 4000 atmospheres) are characteristic of brittle materials which break before entering the region of plastic deformation; in other words, without major deviation from pure elasticity. However, the curves at high pressure (8000 and 10,000 atmospheres) are characteristic of ductile materials which have a 'yield point' on entering the region of plastic deformation, and show a 'work hardening' or increase of strength before rupture takes place." 2000 and 4000 atmospheres confining pressure would be equivalent respectively to depth-loads of 7 and 14 kilometers. Evidently we are not unjustified in considering most limestone replacement deposits as being found in rocks which respond as brittle or semi-brittle materials during their period of "ground preparation," and consequently are justified in studying the deformation of these rocks in the laboratory without the refinement of confining pressures.

Folding, shearing, brecciation, faulting, etc. (the elements of ground preparation) are phenomena undoubtedly related to the relative strength of the various rocks; however, as Griggs has stated (20, p 557), "Strength is a misleadingly simple term." The simplest "strength" to measure probably is the "ultimate crushing strength," *i.e.*, the maximum stress the rock can support before the rupture occurs; consequently tests were made in an effort to correlate the ultimate crushing strength with the favorable characteristics of the ore horizons.

Test Procedure.—The compression tests for determination of the ultimate strength were made in the testing materials laboratory of The Massachusetts Institute of Technology through the courtesy of Professor Irving H. Cowdrey. Standard Riehle and Olsen testing machines of 25, 50 and 100 thousand pounds capacity were used. The machines were manually operated.

Cylinders for the tests were cut from the blocks by means of the same diamond drill used in preparing the discs for permeability tests. All these cylinders were right cylinders $1\frac{5}{8}$ inches in diameter, two inches in length and had carefully polished ends. A hardened steel hemisphere was used as the top bearing plate on the specimen in order to minimize any effects of eccentric loading due either to lack of plane surface at the end of the specimen, or departure from exact parallelism of the end planes. In a few cases diamond drill core of a different diameter was supplied by the mining companies for tests, but the test cylinder length was kept at 2 inches. On the basis of the data given by Johnson (21, p 114, Fig. 7) for cast iron, sandstone, and concrete we might expect an increase of from 5 to 10 per cent in the ultimate strength of cyinders when the ratio of height to diameter of cylinder is changed from 2:7/8 to 2:21/16. These are the maximum variations in the specimens tested in the present study. In the data recorded in Table 9 and

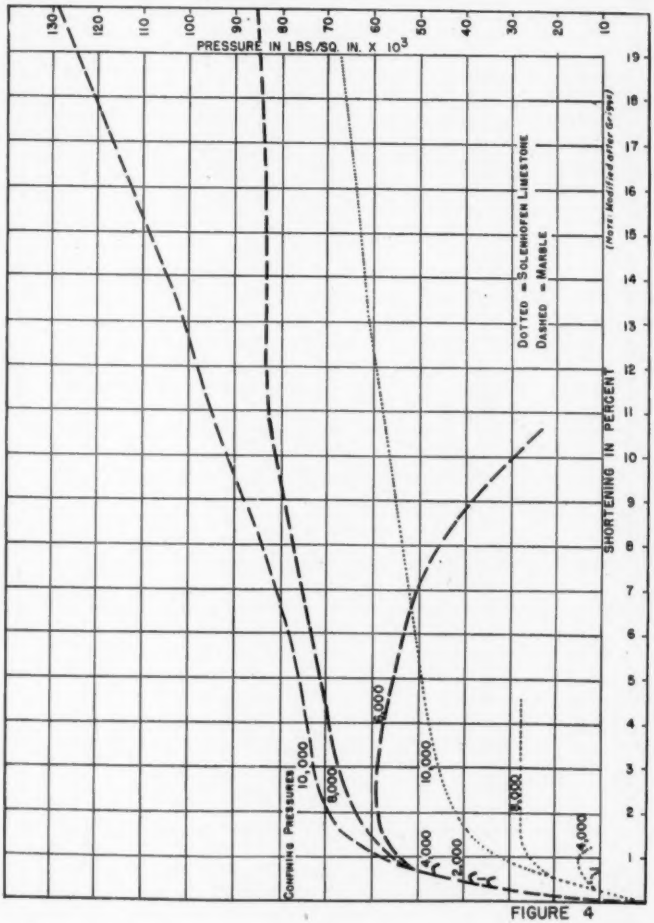
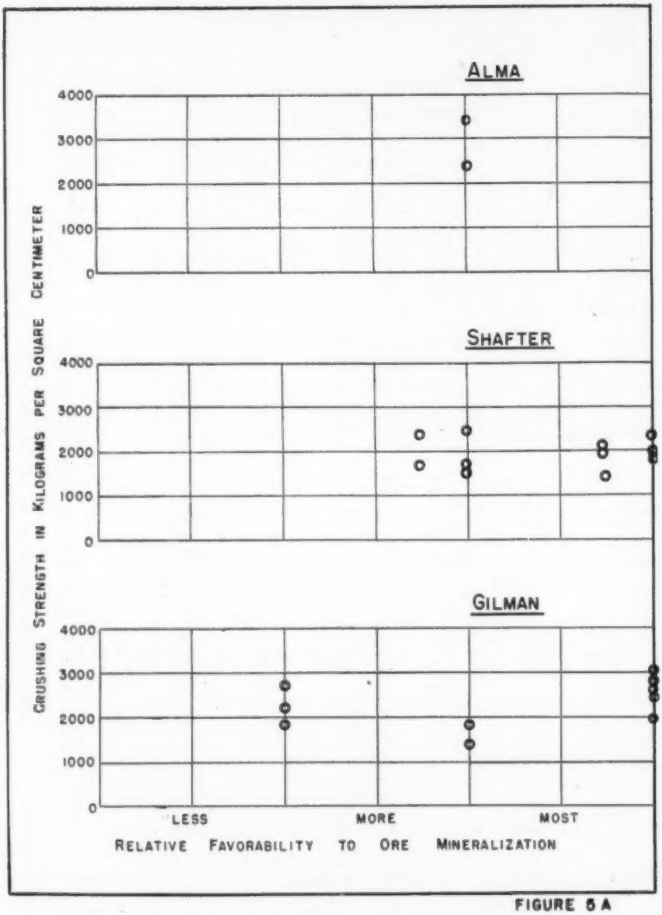


FIG. 4. Deformation characteristics of limestones under different confining pressures.



FIGS. 5A AND 5B. Correlation of crushing strength and relative favorability to mineralization.

plotted in Figs. 5 A and 5 B, no correction has been applied to the original test data.

Johnson (21, p 258, Table 6), quoting Bauschinger's communications, indicates that 8 out of 19 rocks tested parallel to the bedding gave slightly higher results than when tested for crushing strength perpendicular to the bedding. Of the other 11 rocks only 3 or 4 indicate a difference of over 10 per cent in favor of perpendicular to the bedding. (All of Bauschinger's

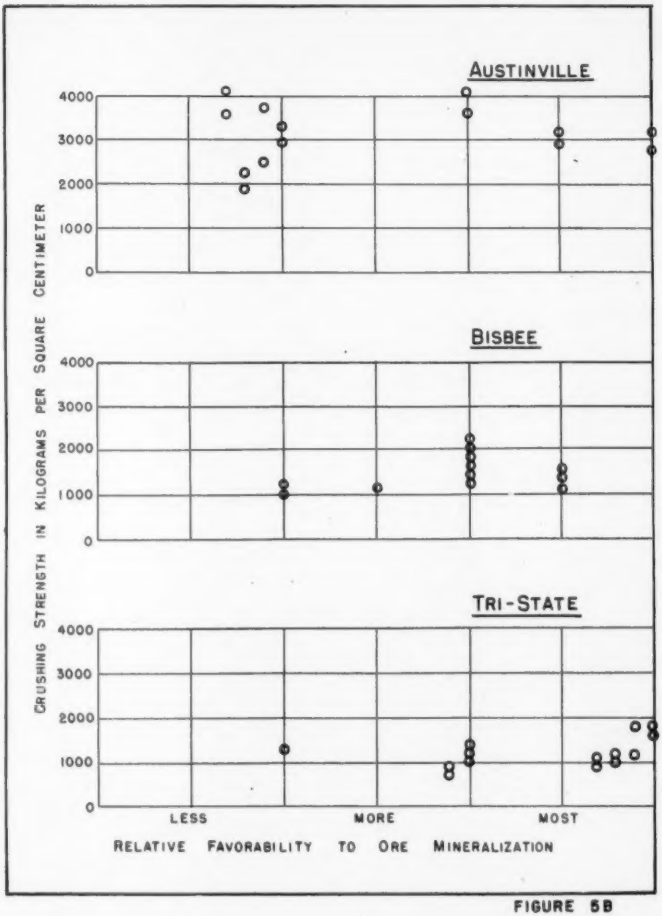


FIGURE 5B

specimens gave appreciable lower values for shearing strength parallel to the bedding than perpendicular to the bedding.) The present tests are in essential agreement with those quoted above, and justify the selection and comparison of cylinders of different orientation. After all, it may be the relative weakness of a rock to shearing or crushing deformation parallel to the bedding which is the significant factor in localizing bedding replacement deposits.

Test Data.—The results of all the crushing tests are plotted in Figs. 5 A and 5 B. The ordinate represents the crushing strength of the cylinders in

kg/cm²; the abscissa has an arbitrary scale with apparent increasing "favorability to ore," to the right of the graph. Each vertical row of points represents a horizon which can be correlated with the data of "ore favorability" in Table 9 by considering the right hand row of points as being horizon 1 (the most favorable), and then numbering the columns of points on the graph consecutively to the left. There appears to be no recognizable and consistent trend indicating increased favorability for either the strongest or the weakest rocks.

On the other hand, an examination of the rupture pattern and the surface of rupture of the cylinders indicated very marked differences, as can be seen in Fig. 6, c, d, e, f, g, h, i. There is a widely accepted belief that different substances show marked differences in the angle of shearing failure in test specimens, the more brittle materials shearing along planes more nearly parallel to the applied stress, or referring to Fig. 7, the shear angle θ is believed to be larger in the more brittle substances. This belief is based upon wide empirical experience which apparently never has been wholly successfully supported by mathematical and physical analysis. As a result several different theories of rupture have been developed which attempt to explain the apparent difference in the observed angle of shearing rupture.

Theories of Rupture.—In reviewing the better known theories of rupture the writer recognized the following series of steps and ideas in earlier experimental work:

(a) Test specimens under compression show a more or less systematic series of surfaces of rupture.

(b) These surfaces of rupture have been observed to approach parallelism with the direction of the applied force, with an increase in brittleness of the test material.

(c) The angle the surface of rupture makes with the direction of the applied force has been measured, and then an effort has been made to compute the position of the surface of shearing failure in terms of the tensile, compressive, shear strength and other characteristics of the materials.

FIG. 6. a. Disc used for permeability tests; b. Fracture pattern of cylinders in impact tests; c. Fracture pattern in crushing strength cylinders, with dominantly extensional failure at left showing Griggs wedge effect, and dominantly shearing failure at right. Middle two cylinders have mixed shear and "tension" failure; d. Tri-State district; crushing strength tests. Cylinders in order from left to right are: 7, 5, 6, 1, 4, 2, 3. Greatest extensional failure at left. 3, 4, 5 and 6 are the most favorable horizons; e. Austinville, Virginia; crushing strength tests. Cylinders in order from left to right are: 9, 5, 2, 2, 1, 8, 3, 4. Greatest extensional failure at left. Most favorable horizons are 1 and 2; f. Shafter, Texas; crushing strength tests. Cylinders in order from left to right are by groups: 3, 4, 1, 2. Greatest extensional failure at left. Horizons 1 and 2 are most favorable; g. Bisbee, Arizona; crushing strength tests: In order from left to right cylinders A, B, C, E, D with greatest extensional failure at left. Relative importance as ore horizons is in decreasing order C, B, A, E, D; h. Gilman, Colorado; crushing strength tests: In order from left to right cylinders 8, 8, 3, 3, 6, 6 with greatest extensional failure at left. Relative importance as ore horizons is in decreasing order 3, 6, 8; i. Alma, Colorado; two cylinders at left are Manitou and Leadville limestones. Right hand cylinder is Lower Blue from Hanover, New Mexico.

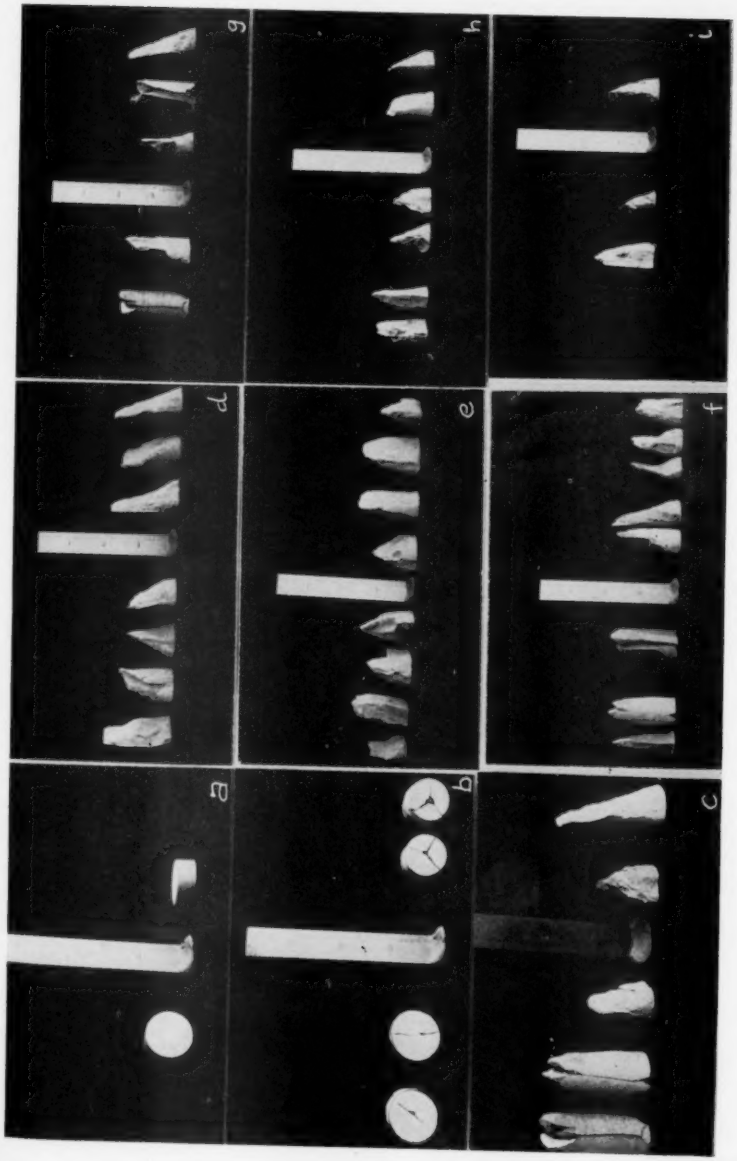


FIG. 6.

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(d) There appears to be one fundamental assumption in this series of steps which is open to question; *i.e.*, that the observed *surface of rupture* really is the *surface of shearing failure* of the material in question.

Mohr's theory of rupture (23, p 9) can be reduced to the formula $\text{Cos } 2\alpha = \frac{C - T}{C + T}$ where T and C are the ultimate strengths of the material in tension and compression respectively, and α is the angle between the plane of shearing failure and the direction of compression. If one substitutes various arbitrary values for C and T in Mohr's equation and solves for Cos 2α, one can construct a graph showing the theoretical relationship between 2α and the ratio C/T. Such a graph is shown in Fig. 7.

The variation in the shear component and the normal component on any plane making an angle α with the direction of compression is shown in the accompanying table (Table 4) taken from Lovering (22, p 712).

TABLE 4.

VARIATION OF THE EFFECTIVE STRESS COMPONENTS OF A COMPRESSIVE LOAD.

Angle α between plane and the direction of compression	Component of Stress (N) normal to the plane ($N = C \text{ Sin}^2 \alpha$)	Component of Stress (S) parallel to the plane (shearing components) ($S = C \text{ Sin } \alpha \text{ Cos } \alpha$)
0°	0.000	0.000
10°	.030	.171
20°	.116	.321
30°	.250	.433
40°	.413	.492
45°	.500	.500
50°	.587	.492
60°	.750	.433
70°	.883	.321
80°	.970	.171
90°	1.000	0.000

Johnson (21, p 258) quotes some data from Bauschinger's "Communications," Volume 10, 1884 on the properties of the building stones of Bavaria. Table 5 contains some of Bauschinger's data, to which the present writer has added the value C/T. Obviously if these values of C/T be referred to the curve in Fig. 7 it will be noted that the angle α will be relatively small, *i.e.*, the rocks are relatively brittle. Becker quotes Rinne as measuring 2α to be 60° for Carrara Marble, while Karman obtained 54° on the same marble, and as low as 38° on a red sandstone. Bucher (23) gives 2α as 20°–30° for his own tests on glass, and quotes Mason as getting 80°–100° for mild steel.

Table 6 is quoted by Johnson (21, p 200) from Bulletin 10, U. S. Department of Agriculture. To this table the writer has added the ratio C/T. From Table 6 it is apparent that 2α for wood will be large, which has been considered as being confirmed empirically by Fig. 3, page 17 in Leith's (24) "Structural Geology."

In summary, it can be said that the relationship between C/T and the shearing angle 2α as expressed in Fig. 7 is at best qualitatively in accordance with the commonly observed data of tests on brittle materials.

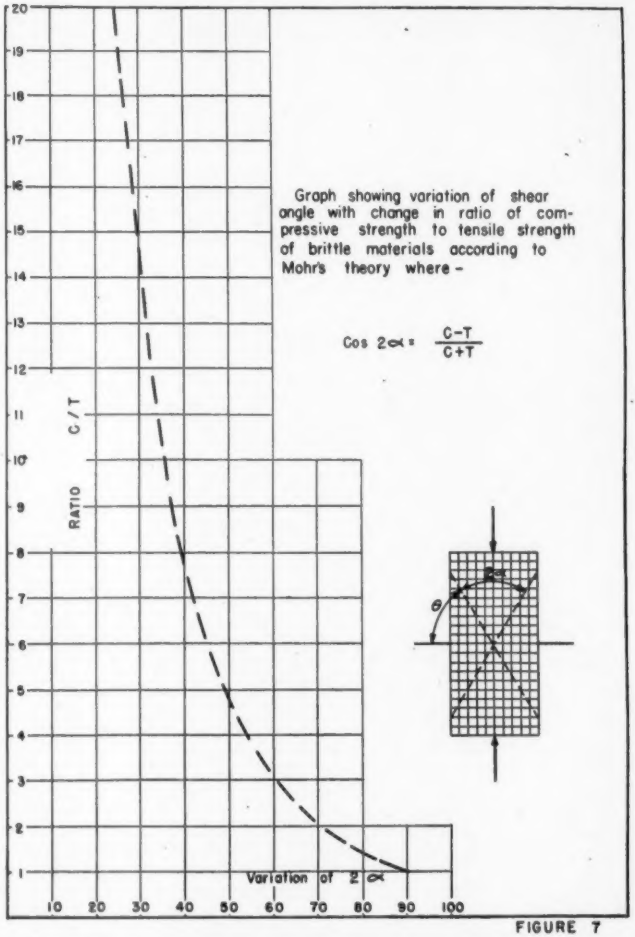

Graph showing variation of shear angle with change in ratio of compressive strength to tensile strength of brittle materials according to Mohr's theory where -
Cos 2α = C-T / C+T
RATIO C/T
Variation of 2α
FIGURE 7

FIG. 7. Variation of shear angle with change in ratio of compressive to tensile strength of brittle materials, according to Mohr's theory.

Griggs' Hypothesis.—Griggs (20, pp 552–557) has presented a very simple and suggestive hypothesis to explain the apparent variation in shear angle so commonly observed in the crushing test failure of brittle test specimens, and the development of the so-called "extension" or tension fractures. Griggs' paper is quoted here at some length:

Types of Fracture: When testing materials in compression, two main types of fractures are commonly observed: "Shear" fractures and "Tension" fractures. The

TABLE 5.

Kind of Stone	Compressive Strength		Shearing Strength		Tensile Strength (T)	C/T	T/S
	Perpendicular to Bed (C)	Parallel to Bed	Perpendicular to Bed (S)	Parallel to Bed			
Granite	19,200	18,910	1,379	142	619	31.	0.45
Granite	19,200	20,050	1,450	853	683	28.1	.47
Triassic limestone	8,130	8,320	555	384	583	13.9	1.05
Jurassic limestone	11,110	7,410	739	540	448	24.8	.61
Jurassic marble	4,664	8,760	498	299	213	21.9	.43
Oolitic limestone	19,340	20,620	1,479	1,138	910	21.2	.61
Tuffa	1,195	2,545	227	213	227	5.3	1.00
Variegated sandstone	7,420	6,010	569	355	107	69.3	.19
Variegated sandstone	9,040	7,790	512	313	199	45.4	.39
Variegated sandstone	12,930	13,410	910	540	576	22.5	.63
Variegated sandstone	6,160	6,100	455	427	128	48.1	.28
Carboniferous sandstone	7,636	8,390	640	284	341	22.4	.53
Carboniferous sandstone	6,684	6,670	583	469	213	31.4	.36
Slaty sandstone	3,071	2,247	370	242	98	31.4	.26
Slaty sandstone	3,029	2,659	242	185	67	45.2	.28
Green sandstone	4,707	4,308	341	327	94	50.1	.28
Cretaceous sandstone	13,510	14,500	668	370	327	41.3	.49
Cretaceous sandstone	28,860	17,490	995	768	512	56.4	.52
Quartz conglomerate	5,546	4,408	—	—	242	22.9	—

TABLE 6.

ULTIMATE STRENGTH.

Species (Hardwood)	Lbs. per sq. inch		Ratios	
	Tension (T)	Compression (C)	T/C	C/T
Hickory	32,000	8500	3.7	0.266
Elm	29,000	7500	3.8	.259
Larch	19,400	8600	2.3	.444
Longleaf pine	17,300	7400	2.2	.428

two can usually be easily distinguished. The former occur when the shear stresses exceed the strength of the crystals and hence are inclined to the direction of compression at about 45°. The surface of the shear fracture usually shows granulation and commonly is slickensided. In rocks it is generally much lighter in color than the tension-crack surfaces, owing to the fracturing and powdering of the crystals. 'Tension' fractures, on the other hand, occur parallel to the direction of compression. Their surfaces are generally cleancut fractures across the crystals with no evidence of granulation or slickensiding.

These so-called tension fractures cannot be explained by the principles of the theory of elasticity. There is no tensile force at right angles to the compression in a homogeneous medium, yet we have abundant evidence that fractures do take place exactly as though there were strong tensile force at right angles to the direction of maximum compression.

There is a very simple hypothesis which seems to explain this type of fracture in many cases. Although it must have been obvious to many men engaged in testing materials the writer has not seen it developed as a hypothesis before. It is this: before rupture, there is a small amount of plastic deformation accompanied

by the development of Luders' lines on the surface of the specimen. These lines seem to be the surface expression of shear surfaces within the specimen. These surfaces in a square prison occur at planes at 45° to all four faces, and distributed fairly evenly over them, with a concentration near the ends. Consequently where any two of these surfaces intersect, a wedge is formed with movement along the shear surfaces causing the development of tension at the point of the wedge. It is in response to this force that the tension cracks develop. This relation between wedges of shear and tension cracks is shown very beautifully in Plate I (Griggs). In this case every tension crack (parallel to the long axis of the specimen) is seen to have a well-developed wedge of shear entering it. Compression was applied longitudinally. The transverse cracks are believed to be due to buckling. Plate IIA (Griggs) also shows the relation between shear wedge and tension fracture. This specimen is the same material (Solenhofen limestone) as the preceding figure, but broken at 4,000 atmospheres confining pressure instead of 1. This is the characteristic type of fracture found in materials slightly less brittle than the Solenhofen, such as concrete, marble, etc.

There has been some question raised as to which came first, the shear crack or the tension crack. Careful observations were made of the failure at atmospheric pressure, and in every case it was observed that Luder's lines developed first and spread slightly before rupture. This is taken as sufficient proof that the shear preceeds the rupture, which takes place with explosive violence when the tension cracks open.

If this hypothesis as to the formation of tension cracks is correct, we would expect them to be inhibited by confining pressure. This follows directly assuming that the liquid has no access to the point of the wedge. In this case the effective tension at the point of the wedge would be equal to the total resolved "tensile" force minus the force due to the confining pressure, so that as the confining pressure is increased, we would expect to come to a point at which no more tension cracks are formed.

Actually, there is very much less tension cracking at high values of confining pressures, but some has been observed even at 10,000 atmospheres confining pressure. Plate IIIA (Griggs) shows a well-developed tension crack parallel to the direction of compression. In all cases it was restricted to a small amount of spalling off of the surface. This spalling is to a large extent responsible for the irregularity of the surface of the specimen in Plate IVA (Griggs).

This inhibition of tension cracks and the corresponding development of innumberable shear surfaces is the most striking effect of the increased confining pressure on the type of failure. In the specimens which seem to have flowed most uniformly (Plate IVB) (Griggs) close examination shows countless shear surfaces inclined at about 45° to the direction of compression. These shear surfaces are analogous to Luders' lines in metals, and probably bear the same relation to the plastic flow of the mass. Another example of multiple shear surface is shown in Plate IIB (Griggs).

When a specimen is sectioned, these shear cracks are seen to be surface phenomena. Thus, when the specimen of Plate IIB (Griggs) was sectioned parallel to the plane of the photograph, the shear cracks were observed to die out as they went inward and the whole central three quarters of the specimen was homogeneous as seen under the microscope. I think there is no doubt that the shearing continues through the center of the specimen. The difference is that at the center where confined on all sides, the shear surfaces never become separated beyond the limit of molecular cohesion, and consequently leave no visible effect.

This seems to indicate that at high pressure failure in the ordinary sense is a near-surface phenomenon. It raises again the question as to whether all faults originated at the surface of the earth and are propagated downward.

Angles of Surface of Shear: It has been stated repeatedly that the angles of the planes of shear failure changed markedly with increasing confining pressure. Kar-

man observed an increase from 27° to 38° 30′ (angle between the plane and the direction of maximum compression) with an increase in confining pressure from 1 to 685 atmospheres. It is extremely difficult to get accurate measurements on the angles of the planes of shear. This can be readily seen by study of photographs showing rupture (*e.g.*, Plates I, IIB and IIIA, in the present paper. Griggs).

A complicating factor in the determination of the angles of the minute planes of shear is the common integration of minute shear and tension fractures to produce a surface whose angle varies from the characteristic angle of the shear surface (nearly 45° to the direction of compression) to that of the tension fracture (parallel to the direction of compression). Sometimes when these surfaces are examined in detail it is possible to distinguish the two types of fractures; occasionally it is possible to get measurements on each one.

Now in some cases this close but often unobservable relation between shear and tension fractures may lead to an erroneous measurement of the angle of shear. Since there is a tendency for tension cracks to be inhibited by the action of confining pressures, of course pressure has a great effect on the angle of this hybrid fracture. In lessening the tension cracks it greatly increases the angle of the surface produced. It may be that this effect has in some cases been mistaken for a true effect on the angle of shear.

The angles of the surfaces of shear as observed in the writer's experiments are not regular enough to warrant quantitative measurements, as can be seen from the photographs reproduced in this paper. However, two general observations may be made: (1) The shear surfaces on which rupture occurs are always inclined to the direction of compression at angles less than 45°; (2) fractures at the highest confining pressures (8,000–10,000 atmospheres) have shear surfaces inclined to the direction of compression at low angles as shown in Plates IIB and IIIA. (Griggs).

Discussion of Griggs' Hypothesis.—The above quoted hypothesis of Griggs is very suggestive in its explanation of the empirical fact that the surface of rupture approaches parallelism with the applied compressive force as the material increases in brittleness. Griggs' suggestion can be depicted as in Fig. 8. In each figure let ab represent the longitudinally applied force on the cylinder which ruptures at an angle θ with the normal to the applied force. The force ab may be resolved into a shearing stress cb on the surface of rupture and a stress ac normal to the surface of rupture. The lateral (or sidewards) component of cb and ac will be equal and opposite, and of a magnitude equal to cd. As Griggs has stated above, there is no external lateral force acting on the cylinder.

The magnitude of the above stresses can be expressed in terms of the applied force and functions of the angle θ. Thus:

$$ab \times \cos\theta = ac = \text{normal component}$$
$$ab \times \sin\theta = cb = \text{shear component}$$
$$cb \times \cos\theta = cd = \text{lateral component of cb}$$

cb and ac are equal in magnitude, but act in opposite directions. But $cd = ab \times \sin\theta \cos\theta = \frac{\sin 2\theta}{2}$. If now we consider the applied force ab as unity the above mentioned stresses are expressed directly as the functions of the angle θ.

According to Hooke's law, under conditions of stress below the elastic limit, the strain is approximately proportional to the stress. If then in Fig.

8, and the above discussion, we think of ab as being the vertical strain due to an applied stress we find that the cb is the strain parallel to the shear plane and cd is the total lateral component of strain. The strain component

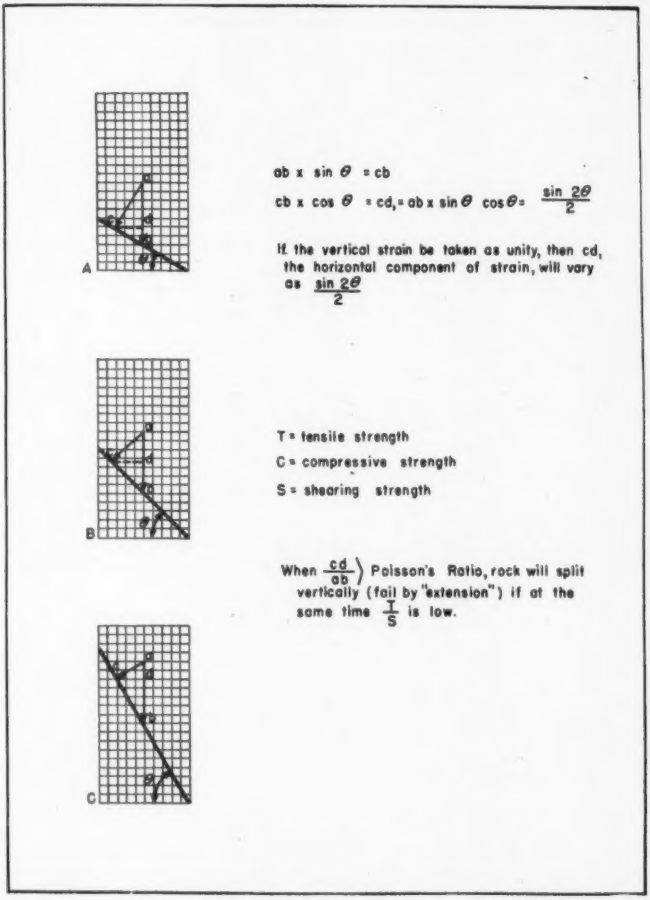

A
B
C
ab x sin θ = cb
cb x cos θ = cd, = ab x sin θ cos θ = sin 2θ / 2
If the vertical strain be taken as unity, then cd, the horizontal component of strain, will vary as sin 2θ / 2
T = tensile strength
C = compressive strength
S = shearing strength
When cd/ab ⟩ Poisson's Ratio, rock will split vertically (fail by "extension") if at the same time T/S is low.
FIGURE 8

FIG. 8. Graphic explanation of Grigg's hypothesis.

cb is related to the force Griggs refers to in the preceding quotation in the following terms: "Consequently, where any two of these surfaces intersect, a wedge is found, with movement along the shear surfaces causing the development of tension at the point of the wedge. It is in response to this force

that the tension cracks develop." Such a failure caused by excessive strain has been called "extension" failure by Bridgman in contrast to a true "tension" failure caused by excessive stress resulting from a direct force. That is, this fracture is not the result of a direct externally acting force, but the result of an indirect internal strain caused by an external force.

The strain $\frac{cd}{ab}$ is referred to as Poisson's ratio, and as can be seen by reference to Fig. 8 reaches a maximum when θ is 45°. If, as is commonly believed, the stress component ac normal to the surface of rupture creates a frictional resistance on the shear plane which tends to steepen the angle of rupture, then as the angle of rupture is steepened the lateral component of strain cd which is developed along the shear plane is lessened. This would be contrary to the tendency implied by Hooke's law, and it would seem reasonable that the failure would take place on a shear plane giving maximum release to the strain cd, *i.e.*, at 45° to the applied force.

Or in Becker's words (25, p 48), "In a homogeneous mass under pressure, rupture must take place on the lines of maximum tangential strain: for rupture is strain carried to such an intensity that cohesion is overcome."

Zisman (26, p 659) has demonstrated that at atmospheric confining pressure Poisson's ratio increases appreciably with increase in applied load. The data for Rockport granite are quoted here:

Mean Load in Pounds	Poisson's Ratio
0	0.084
1000	.093
2000	.102
3000	.111
4000	.120
5000	.129
6000	.138
7000	.149
8000	.159
9000	.172

This too would seem to be contrary to the idea of a steepening angle of shear rupture with increase in applied load, as the lateral strain is increasing faster than the longitudinal strain.

The vertical splitting is an expression of failure by "tension" due to the "spreading apart" or "extension" at one of the shear wedges to which Griggs refers. *This condition will evidently be reached when Poisson's ratio increases to and exceeds the ratio* $\frac{T}{S}$. In other words, if this wedging strain causes a local stress in excess of the tensile strength of the rock *before* the maximum shearing strength of the rock is reached, the rock is going to split or tear, giving vertical tensile or extensional surfaces of rupture. If $\frac{T}{S}$ is small the initial split will probably be propagated through the whole length of the specimen, especially if we are dealing with a compact, brittle fine-grained rock such as the Solenhofen limestone. If $\frac{T}{S}$ exceeds unity the rock will fail by shearing rupture. If $\frac{T}{S}$ is less than, but approximates unity,

the rock will probably fail by shearing, or minute alternations of shearing and tension, especially if the rock is medium to coarse grained, rather than dense fine grained.

Griggs states (20, p 555) that: "The angles of the surfaces of shear as observed in the writer's experiments are not regular enough to warrant quantitative measurements, as can be seen from the photographs reproduced in this paper (Griggs). However, two general observations may be made:

(1) The shear surfaces on which rupture occurs are always inclined to the direction of compression at angles less than 45°.
(2) Fractures at the highest confining pressures (8000–10,000 atmospheres) have shear surfaces inclined to the direction of compression at low angles as shown in Plates IIB and IIIA."

Griggs notes further (20, p 555) that a complicating factor in determining the angle of shear is the "common integration of minute shear and tension fractures to produce a surface" which varies from about 45° to 90°; but that if examined in detail it is sometimes possible to distinguish the two types of fractures and get measurements on them. And further, that increased confining pressure lessens the tendency to form the tension cracks and hence "has a great effect on this hybrid fracture."

Of the material tested in the present study it was observed that all those specimens which gave a steep angle of rupture were the finest grained, while those that gave a rather even sloped rupture surface extending approximately diagonally across the specimen were the coarsest grained. This observation may be correlated to the type of fracture and Griggs' hypothesis if we visualize the possible development of a vertical tension fracture in the coarse-grained rock as being minutely interrupted by cleavage or other planes of weakness in the different orientations of the relatively large crystals. In the case of the different orientations of the fine crystals the effect of the small crystals is not sufficient to be significant, and hence the rupture surface is not modified.

In summary: Owing to the usually low tensile strength of rocks it is probable that under all such compression tests on brittle materials as herein referred to, the wedge effect producing tension results in minute tension failures which, even on a molecular scale, affect the angle of rupture so that the true angle of shearing failure seldom coincides closely with the observed surface of rupture. *Consequently the writer would suggest that the true angle of shearing failure is for all practical experimental purposes a theoretical concept occurring at 45° to the applied stress, and is seldom observed unmodified by tension failure, while the true "tension" fracture probably is frequently observed, with only minor modifications by the shear fracture.* And further, that the commonly observed surface of rupture is but an integration of the relative amounts of shear and tension failure which controlled the fracture, and as such is more or less characteristic of each material in determining the type of failure which will be produced. It is the surface of rupture which varies in steepness; not the surface of shearing failure. This steepness is a function of $\frac{T}{S}$.

Up to the elastic limit rocks will approximately follow Hooke's law, but past this stress, continued deformation depends on whether the rock behaves brittlely or plastically. Brittle materials permit little or no increased strain before rupture; plastic materials may suffer appreciable deformation beyond the elastic limit before rupture. *It is known that in general brittle materials have low values of Poisson's Ratio, and the writer would suggest a possible correlation of this low ratio with a low value of* $\frac{T}{S}$, *and a correspondingly high value for the angle* θ *defining the position of the surface of rupture.*

Discussion of Crushing Strength Tests.—As has been discussed, it is common practice in crushing tests to examine the fragments of the original cylinder and measure the angle the surface of rupture makes with the normal to the applied force. In following this procedure, the writer found it essentially impossible to isolate for measurement, any surface that could be clearly identified as a shear surface. Every surface observed showed some evidence of tension fracturing as well as shearing. This led to the analysis of the theory of rupture and the discussion given on the preceding pages.

Attempts made to measure the "angle of rupture" were, however, very suggestive though yielding no specific measurements. Examination revealed two extreme types—one in which extensional fracturing appeared to dominate, and another in which extension was not prominent, so we may say shearing dominated. Gradation from the one extreme to the other was quite evident in the different suites. The extreme types and an intermediate type are shown in Fig. 6, c. An attempt was made to arrange the specimens in a series showing decreasing extensional failure. Little difficulty was experienced in deciding on the relative order of the specimens near the dominantly extensional end of a series, however, at the end where shear failure tended to dominate, observers did not always agree on the relative position of the individual specimens. Nevertheless, the evidence of a variation, or trend, from dominantly vertical extensional fracturing to dominantly inclined shear fracturing was convincing, as can be seen in Fig. 6, c.

If one examines critically these series of cyinders with regard to their surfaces of rupture or "shear" it will be noted that, in general, the finer the grain of the rock, the steeper the angle of rupture, *i.e.*, the greater the proportion of extensional failure to shear failure. For the same reason that it has always been found difficult or impossible to measure the presumed angle of "shear" failure, it is also difficult to measure the angle of rupture. Nevertheless while individual specific measurements may lack in conviction, the series, when studied as a group, indicate a definite trend.

An effort was made to correlate the different types of fracture with the known relative favorability to ore. This study indicated that those specimens at the extreme end of the series in which extensional fracture dominated were always less favorable than those in which tension and shear failures were intimately associated. The extreme shearing failure end of the series also appeared to be somewhat unfavorable, though the evidence was less convincing than in the case of the extensional failure specimens.

In detail examination the most favorable limestones exhibited very intimate alternation of tension and shear rupture *throughout the major part* of the specimen. The rock as a *whole* was shattered, resulting in a loose porous and permeable structure with appreciable fines. When extension dominated, evidence of a shear wedge or cone would be confined to a small section near one or both ends. The rest of the specimen would be in the form of large splinters, either triangular or rectangular in section, sometimes with distinct conchoidal fractures leading out from the shear cone very much as Griggs has described it. The surfaces of fracture were essentially vertical, and smooth. The specimens broke with explosive violence. When shearing dominated, the specimen separated quietly into two asymmetrical cones with practically no fines or intermediate-sized pieces; the surface of rupture, however, did show appreciable fines. These three types are shown in Fig. 6, c.

The one extreme represents a fine-grained, compact, relatively strong rock; the other a relatively coarse-grained, loosely knit weak rock. The former would be referred to as a competent rock; the latter as an incompetent rock. Under comparable conditions of deformation the most competent rock will probably develop but few fractures, which will be relatively clean-cut and free from sympathetic shearing in the adjoining rock. The least competent formation will probably crumple and fold readily, *i.e.*, types of deformation that call dominantly for shearing rather than tension rupture, and, where fractured, may develop appreciable gouge along the shear planes. Intermediate between these two extremes are those rocks which show widespread zones of sympathetic fracturing, sheeting, and brecciation associated with fault zones, and which undergo some folding, but do not develop detailed crumpling.

Interpretation of Significance of Crushing Strength Tests.—While it has been impossible to make any quantitative correlation between the few data available from the crushing tests and the ore distribution, some significant suggestions can be inferred.

It was noted on an earlier page that it was the dense, fine-grained rocks with high elastic limits that broke with the characteristic extensional rupture. These are the very brittle rocks; rocks which will approach the characteristics of the Solenhofen limestone of Griggs' experiment. They are mostly competent and strong. Because of their high crushing strength, and frequently low ratio of tensile to crushing strength, it may be expected that these rocks will commonly develop tension joints or faults, and en echelon fractures, all of which are characterized by the development of (and apparent maintenance of) open spaces, and a minimum amount of associated sympathetic sheeting or fracturing. There will be but little development of fines, because there is little associated crushing or shearing. Such fractures are easily entered by ore solutions, but the very compact impervious character of the wall rock will result in little replacement; the ore deposits are essentially open space fillings of the fracture type rather than bedding replacement deposits.

If on the other hand a coarse-grained rock of low crushing strength, and generally of high ratio of tensile to shearing strength, rupture of the rock may commonly result in the development of an important amount of faulting characterized by shear zones with possible development of heavy gouge.

Under these conditions all adjustment to stress is in the form of a strain that has the tendency to crush and pulverize the rock because of the grinding and shearing action involved, and at the same time to *close* openings in the rocks, rather than create new openings. Under extreme conditions faults in such rocks may be less pervious than the unfaulted rock, and have in some cases been interpreted as barriers to ore migration rather than as ore solution conduits (27).

In contrast to the two above discussed extremes, in a medium-grained rock in which the tensile strength and shearing strength are approximately equal we may expect intimately associated shear and tension failure, resulting in an intimately shattered rock. Under these conditions there may be a relatively large amount of grinding and crushing (production of fine material), and at the same time a development and maintenance of some relatively free, open and permeable channel ways. The analogy might be drawn between a fine-grained dense brittle rock and a sand in "close packing"; *any deformation tends to create new openings and necessitates an increase in volume* (39). On the other hand a coarse-grained easily recrystallized limestone, or other rock easily deformed by flowage, resembles a sand in "loose packing"; *any deformation tends to close existing openings or at least modify them.* In the first case there would be a tendency to "suck" in any solutions available to the openings. In the second case solution access would be hindered, or if already present, the solutions, if still in fluid condition, might migrate. A rock undergoing mixed tension and shear deformation would have the advantage of favorable host rock through the creation of easily replaceable fines, increased permeability through the development of new openings, and the possibility of ore fluid migration during deformation. This feature of alternating tension and shear deformation appears to result in a wide distribution of the resulting fractures. It is probable that a horizon having the above qualities, as contrasted with the over and underlying weaker or stronger beds, would show a much wider fracture zone than the adjoining beds. This would result in a widening of the zone of possible mineralization, which under favorable conditions, such as associated thrusting, might initiate bedding replacement deposits.

The influence of the type of rock on the character and degree of fracturing, folding and general deformation of rocks, and consequently "ground preparation," is too well recognized to warrant any detailed discussion here. Good summary discussions, and references to specific cases, will be found in Spurr (28, especially Chaps. 3, 7), Emmons (29, especially Chap. 17), Lindgren (30, especially Chaps. 11–13), and in Stoces and White (31). The literature is replete with general qualitative data on the behavior of rocks during the period of "ground preparation" in various mining camps. It is probable that many of these data could be organized into a systematic statement on the relative ease of "ground preparation" and importance of mineralization, which could be correlated at least qualitatively with the known laboratory data on the physical constants of similar rocks.

However, a specific quantitative study of the behavior of the different rocks in a mining camp under similar conditions of deformation, appears to

be lacking. It is hoped that the investigations reported on in this paper will be sufficiently suggestive of the possibilities to encourage such studies. A quantitative screen size record of the material produced in crushing tests would also be of interest. It would be particularly interesting to see more of the high confining pressure studies of the Bridgman-Griggs type performed on selected material from different deep mines where the natural behavior of the rock is well known.

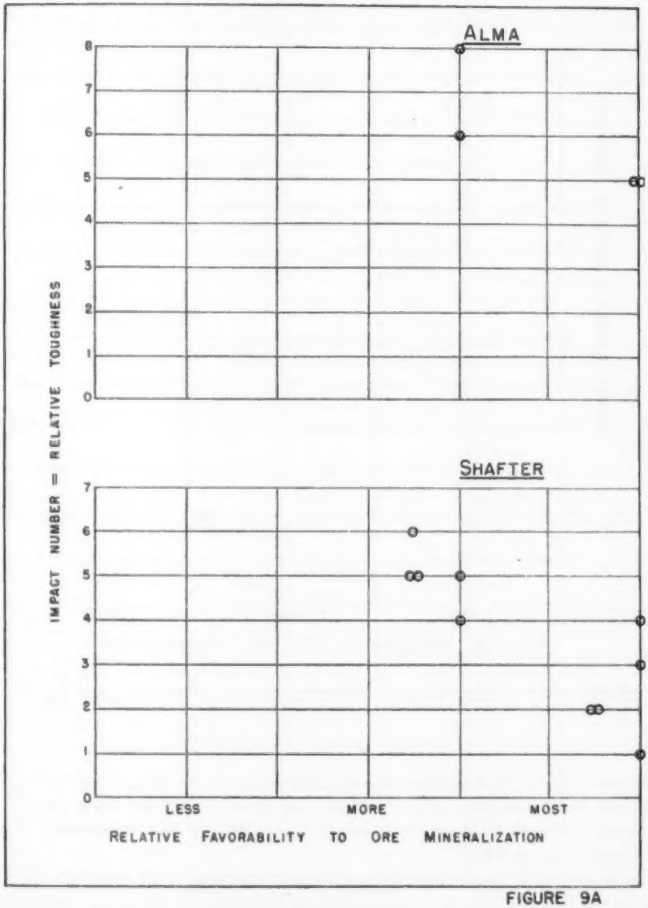


FIGURE 9A

FIGS. 9A, 9B AND 9C. Correlation of toughness and relative favorability to ore mineralization.

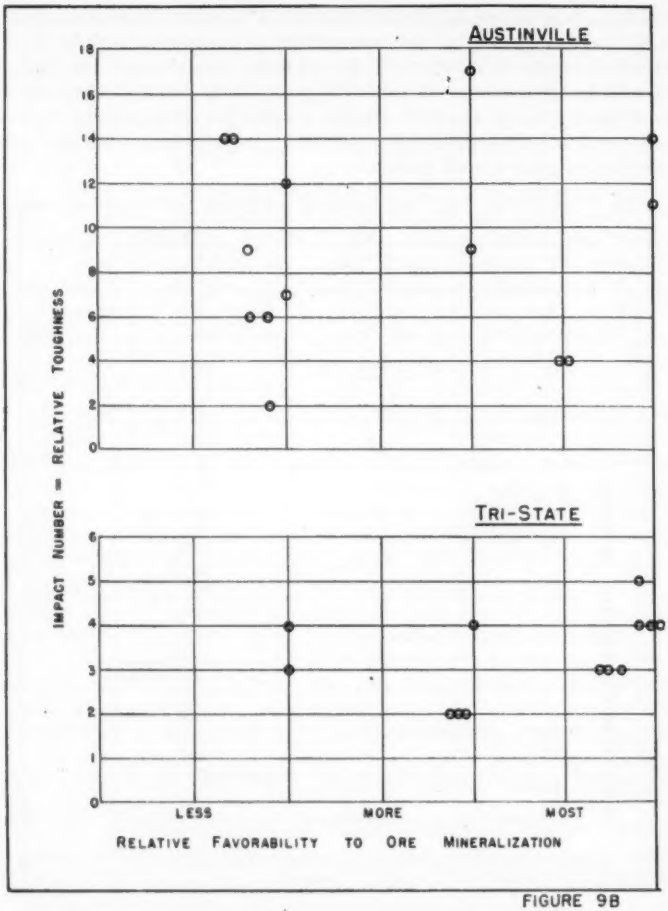


FIGURE 9B

TOUGHNESS TESTS.

Introduction.—"Toughness, as applied to rock, is the resistance offered to fracture under impact, expressed as the final height of blow required of a standard hammer to cause fracture of a cylindrical test specimen of given dimensions" (32, p 94).

The test is performed on a Page impact machine (33, pp 153–155). A standard-sized specimen of cylindrical shape, 25 mm in diameter, and of equal length is used. This cylinder is held in place on a steel anvil while a kilogram hammer (having a spherical lower end) is dropped on the specimen.

The first blow is from a height of 1 cm; by means of a sprocket chain the hammer is automatically raised to 2 cm and dropped, then to 3 cm etc., until the specimen splits. The toughness is expressed in the height of final blow required for rupture.

Johnson (21, p 6) says that "Tough materials will withstand heavy shocks or will absorb a large amount of energy." Toughness is dependent upon strength and ductility, or strength and flexibility. Mild steel, wrought iron, and hickory are tough materials.

This would imply that brittle materials are not tough, and according to ordinary usage that is correct. However, the fact that "strength" also enters

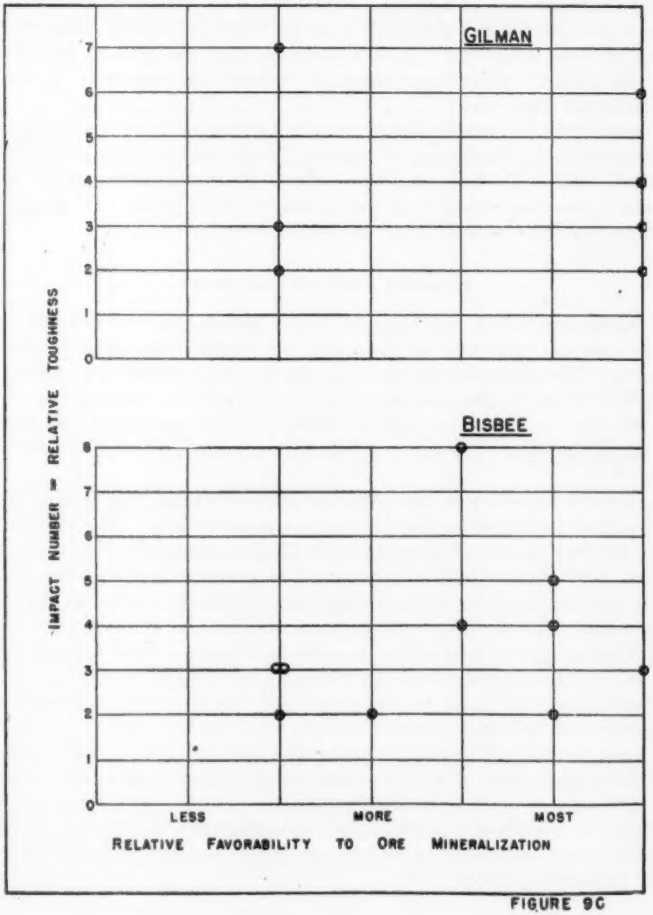


FIGURE 9C

into the definition results in it being possible for some brittle substances, such as certain rocks, also to be tough. The property is one that does not lend itself to exact definition or measurement; it is a relative term.

Test Data.—The test data on the impact experiments are itemized in Table 9 and summarized graphically in Fig. 9.

All specimens used were of uniform height, but, as mentioned under permeability, some of the drill core furnished was not of uniform diameter. The writer has found no correction factor for application to the non-standard-sized cylinders. Only the drill core from Austinville was not all of the same diameter.

If we assume that an increase in diameter of the test piece would result in a too high figure on the toughness scale we could arbitrarily lower the rated values of these specimens. Such adjustment does not seem to improve possible correlation, excépt in so far as it reduces the toughness of the most favorable ore horizons.

No consistent or usable correlation of toughness and ore favorability could be demonstrated. In the case of Shafter, Texas, only two horizons were represented, each with two specimens. Both of the most favorable horizon specimens were less tough than the unmineralized horizon. In all the other districts there was no semblance of correlation.

RELATIVE GRINDABILITY TESTS.

Introduction.—Mill men engaged in ore dressing have developed a more or less standard procedure for measuring the relative grindability of the various ores. The essence of the test is to take a given amount of material, grind and screen under similar conditions and then plot curves showing the relationship between the per cent weight through one screen and caught on the next, and the screen size. The curves show marked variation for different types of ores.

It seemed possible that one might be able to correlate this relative grindability with the relative ore distribution in a given district. The thought back of the test was the possibility that under similar conditions of "ground preparation" different amounts of fines would be produced in the different rocks, which was suggested by the crushing tests mentioned earlier in this paper. And further, that the relative abundance of fines (if not compacted into an impervious gouge) would affect the ease of solution and replacement of the rock by the ore solutions, and also the ease of migration of the ore solutions.

Theoretically (34), in dealing only with limestones there should be no difference between one limestone and the next for they are all composed of the same mineral. However, actually they are not pure calcite limestones of uniform character. The limestones are of different grain size, and have different areas of inter-crystalline contact, the arrangement (degree of interlocking) of the inter-crystalline contact is different, differences in porosity probably exist, and finally there are differences in the degree and character of the impurities present.

The tests were conducted in The Richards Ore Dressing Laboratory of The Massachusetts Institute of Technology through the courtesy of Professor Charles E. Locke, and Mr. Reinhardt Schuhmann, Jr.

Description of Test.—The test procedure was as follows: The rock specimen was broken up into pieces containing from 1 to 4 cubic inches. These pieces were put through a small jaw crusher set with $\frac{3}{8}$ inch opening, and this product in turn was crushed down on a bucking board until 500 grams of the desired product was obtained. The charge was put in a small porcelain ball mill together with 500 grams of water and 3000 grams of porcelain balls

TABLE 7.

SCREEN PRODUCTS FROM GRINDING TESTS ON BISBEE LIMESTONES.

Size Mesh and Elutriation Products	14–28	28–35	35–48	48–65	65–100	100–150	150–200	E_1	E_2	E_3	E_4
Ave. Dia. in Microns	879	503	356	252	178	126	89	45	16.0	5.6	2.0
Specimen No. A											
Grams Rec.*	11.8	8.3	9.1	9.0	11.1	9.0	7.6	20.9	12.5	12.5	12.5
% Rec.	9.4	6.6	7.3	7.2	8.9	7.2	6.1	16.7	10.0	10.0	10.0
Specimen No. B											
Grams Rec.				0.1	0.1	1.1	4.0	41.8	34.5	33.5	9.6
% Rec.				.1	.1	1.0	3.8	33.4	27.6	26.8	7.6
Specimen No. C											
Grams Rec.	7.6	1.4	0.8	0.9	2.8	12.1	24.1	35.4	13.4	17.3	7.8
% Rec.	6.1	1.1	0.6	0.7	2.2	9.7	19.3	28.4	10.6	13.9	6.2
Specimen No. D											
Grams Rec.				0.1	0.1	1.2	4.8	45.0	30.8	33.2	9.5
% Rec.				.1	.1	1.1	4.5	36.0	24.6	26.6	7.6
Specimen No. E											
Grams Rec.				0.1	0.3	2.2	7.1	35.2	23.9	42.0	12.5
% Rec.				.1	0.2	2.0	6.5	28.2	19.1	33.6	10.0

* Indicates "Recovered."

ranging from $\frac{1}{2}$ to 1 inch in diameter. The ball mill was rotated for exactly $\frac{1}{2}$ hour at 71 r.p.m., after which the material was washed into an enameled dish and evaporated to dryness on a steam bath. The product was quartered in a sample cutter, and the selected quarter screened wet on the 200-mesh screen. Both the fines and the coarse were dried, and the coarse then placed on a set of standard Tyler screens and put in the "Ro-tap" for 10 minutes. The different fractions were weighted, and the two minus 200-mesh products added together.

The measurement of size distribution in the minus 200-mesh material is at best a tedious and difficult task. The writer is greatly indebted to Dr. Alan Lukens and Mr. William Priestley of the Thompson, Weinman Research Laboratories in Cambridge for undertaking this task by means of a special hydrometer technique utilized by them in connection with the preparation of pulverized limestone.

The data of the grinding tests are itemized in Table 8, and expressed graphically in Fig. 10. These graphs were interpreted as indicating no usable correlation between the relative grindability as conducted in these tests, and ore distribution. This is particularly true for the Tri-State district, while in the case of Bisbee there is partial correlation. Thus horizon C of the Bisbee district, which is the most favorable horizon, was not ground as fine as the least favorable horizon D, nor left quite so coarse as A which is intermediate in ore favorability. On the other hand, horizon B, the second most favorable horizon is essentially identical with the two least favorable horizons, D and E.

TABLE 8.

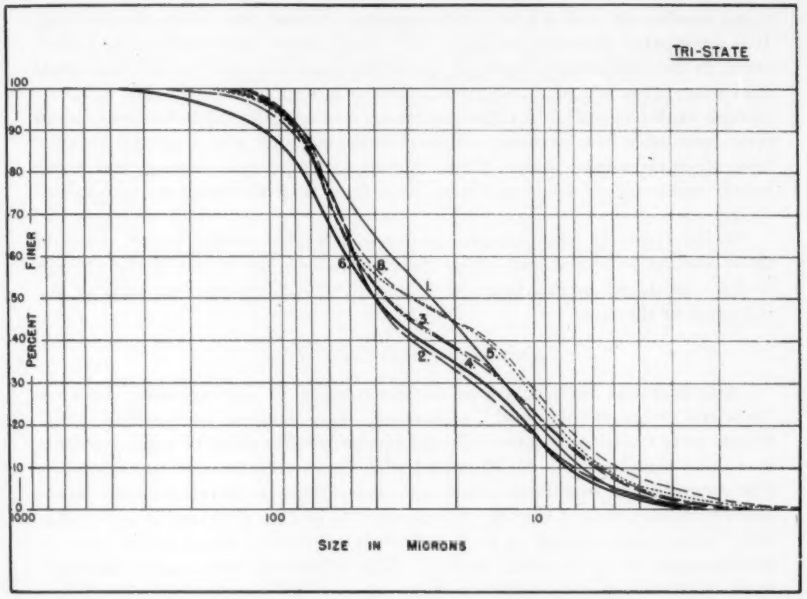
SCREEN PRODUCTS FROM GRINDING TESTS ON TRI-STATE LIMESTONES.

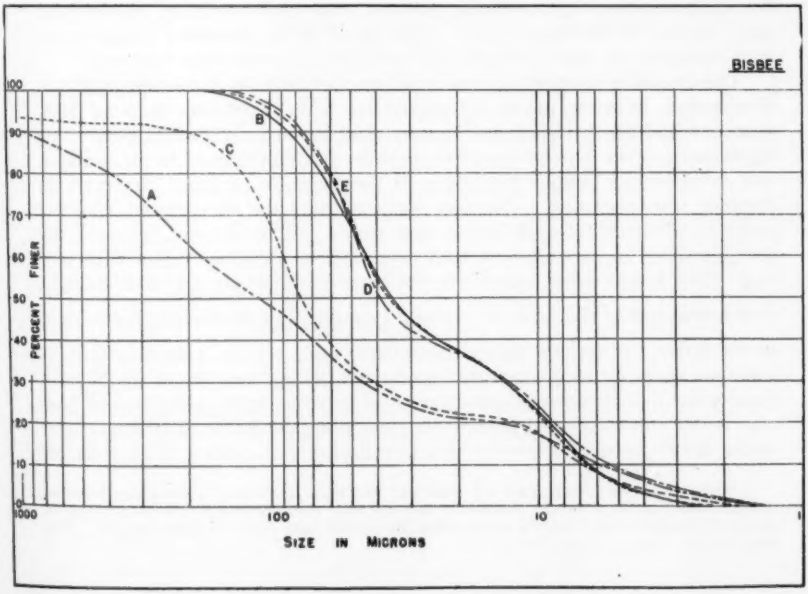
Size Mesh and Elutriation Products	14–28	28–35	35–48	48–65	65–100	100–150	150–200	E_1	E_2	E_3	E_4
Ave. Dia. in Microns	879	503	356	252	178	126	89	45	16.0	5.6	2.0
Specimen No. 1											
Grams Rec.*	.0	.1	.0	.1	.1	1.2	4.1	31.1	39.4	37.0	11.9
% Rec.		.1		.1	.1	1.0	3.3	24.9	31.6	29.6	9.6
Specimen No. 2											
Grams Rec.	.0	.1	.0	.1	.1	2.0	6.6	43.7	35.7	27.6	8.1
% Rec.		.1		.1	.1	1.6	5.3	35.0	28.6	22.1	6.5
Specimen No. 3											
Grams Rec.	.1	.1	.1	.1	.1	1.3	5.0	48.5	26.0	31.9	11.8
% Rec.	.1	.1	.1	.1	.1	1.0	4.0	38.8	20.8	25.5	9.5
Specimen No. 4											
Grams Rec.	.0	.1	.0	.1	.2	1.2	4.5	42.8	29.8	33.4	13.1
% Rec.		.1		.1	.1.6	1.0	3.6	34.2	23.8	26.6	10.5
Specimen No. 5											
Grams Rec.	.0	.1	.0	.1	.1	1.5	5.6	41.5	23.0	39.2	11.5
% Rec.		.1		.1	.1	1.2	4.5	33.1	18.5	31.4	9.2
Specimen No. 6											
Grams Rec.	.0	.1	.0	.1	.4	3.1	8.3	40.8	29.4	31.7	11.3
% Rec.		.1		.1	.3	2.5	6.6	32.6	23.5	25.4	9.1
Specimen No. 8											
Grams Rec.	.0	.1	.0	.1	.5	2.6	6.9	37.4	30.6	31.2	14.2
% Rec.		.1		.1	.4	2.1	5.5	29.9	24.5	24.9	11.3

* Indicates "Recovered."

Discussion of Grindability Tests.—It was concluded that the test as conducted was not satisfactory in that the material had been ground too fine. The following modification is suggested as warranting a trial before condemning grindability tests for correlating purposes.[6] With 5 or 10 times as much original material available, break the field specimen into fairly uniform pieces of say 2 to 3 cubic inches in volume. Put these pieces through

[6] See United States Bureau of Mines, Report of Investigation No. 3390 on "Primary Crushing," by Mark Sheppard, 1938, for a preliminary study of this character.





FIGS. 10A AND 10B. Grinding characteristics of favorable and unfavorable limestones.

a jaw crusher set with a $\frac{1}{2}$ to $\frac{3}{4}$ inch opening. Screen and weigh this product. It is anticipated that this procedure will much more clearly reflect the differences in the competency, strength, brittleness, and elasticity of the individual horizons. This test may suggest whether or not enough fines would be made along a fault to result in a tight breccia zone filled with excessive fines, or an open permeable breccia zone with only moderate fines and a greater proportion of intermediate sizes. The compact, fine-grained, strong and more brittle rocks will probably produce fewer fines than the weak coarse-grained rocks.

In the crushing strength tests, as reported earlier in this paper, it would be of interest to screen and weigh the crushed cylinder to see if the amount of fines produced in this test are related to ore distribution as well as the character of the rock.

SUMMARY AND CONCLUSIONS.

Attention has been called to the importance of distinguishing between "primary" intergranular and "secondary" deformational permeability. Attempts were made to measure only the former in this series of tests, resulting in values ranging from 0.004 millidarcys to essentially zero permeability. The measured permeabilities could not consistently be correlated with favorable ore characteristics, and the values were so low as to minimize the probability of any long distance or large volume intergranular migration of the ore-bearing solution in the rocks tested.[7] *The relative greater ease of development of secondary permeability in favorable ore horizons probably dominates the mass migration of ore-bearing solutions into these horizons, resulting in their greater ore-bearing record. Only from these secondary channelways does intergradular pore permeability probably play any important role.*

The crushing strength values could not be directly correlated with ore distribution, however, there did appear to be a correlation between rock character and type of specimen rupture, and in turn ore distribution. The significance of the type of specimen rupture was emphasized in an analysis, and extension, of Griggs' hypothesis of the origin of "tension" fractures in crushing test specimens. The tests suggested that the fine-grained, compact rocks were strong, though brittle, and would fail by tension, whereas the coarse-grained rocks were weak and would fail by shearing, rather than tension. The former were competent, the latter incompetent, and it is thought that in the former the ratio of $\frac{T}{S}$ would probably be considerably lower than in the latter. If tension failure dominates, gash veinlet structures will be common, resulting in dominantly "open-space filling" ore bodies of the vein type; while if shearing dominates, excessive grinding with production of fines may result in a compacted impervious zone along the fault. *The importance of the development of a porous structure during deformation is emphasized,*

[7] During discussion Bannerman has suggested that the migration of mineralizing solutions through intergranular pores simultaneously with the structural adjustments the rock undergoes during deformation may be much greater than the present tests on permeability suggest. This idea is closely akin to Mead's (39).

TABLE 9.

COMPOSITE TABULATION BY DISTRICT OF ALL TEST DATA ON PERMEABILITY, IMPACT NUMBER, AND CRUSHING STRENGTH.

Note: The orientation of the test is indicated by the letter under "Remarks." Thus: B signifies normal to bedding. S signifies parallel to strike. D signifies parallel to dip.

Bisbee, Arizona

Horizon and Number	Ore Favorability	Permeability		Remarks	Impact Number	Remarks	Crushing Strength Kg/cm²	Remarks
		Disc	Millidarcys					
Upper Escabrosa (E)	4	25	.0000029	S	2	B	1150.	B
		26	.000011	S				
		27	.0000014	S				
		28	.0010	Stylolite				
		29	.00065	Stylolite				
		30	.0000018	B				
		31	.0000021	B				
		32	.0000026	B				
		33	.0000017	D				
		Ave.	.0000034	(omitting 28 & 29)				
Middle Escabrosa (D)	5	50	.000005	B	3	B	1030.	B
		51	.0000075		3	B	1070.	S
		Ave.	.0000062		2	D	Ave.1050.	
Lower Escabrosa (C)	1	40	.0000021	S	3	S		
		41	.0000026	S				
		42	*	D	1	D	1020.	D
		43	.0000007	D	cracked (?)		2130.	B
		Ave.	.0000016	(omitting 42)			Ave.1580.	
Martin (upper half) (B)	2	34	.000004	S	2	S	1320.	S
		35	.0000037	S				
		36	.000010	B	4	B		
		37	.0000027	B			1480.	D
		38	.0000034	D	5	D	1130.	D
		39	.0000029					
		Ave.	.0000038				Ave.1305.	
Abrigo (A)	3	44	.000002	B	4	B	2030.	Minor silicifi- B
		45	.0000011	B	8	B	2050.	cation in all B
		46	**	D			1190.	specimens. D
		47	.0000029	D			1340.	Bedding D
		48	.0000005	S			1870.	shows in all S
		49	.0000046				1420.	specimens
		Ave.	.0000022	(omitting 46)			Ave.1650.	

Note:

* Impervious: No change in 7 hours.

** Impervious: No change in 11½ hours.

TABLE 9.—*Continued.*

Austinville, Virginia.

Horizon and Number	Ore Favorability	Permeability		Impact Number	Remarks	Crushing Strength Kg/cm²	Remarks
		Disc	Millidarcys				
#1	3	79	.0000074	17	$1\frac{5}{16}$" dia.	4125.	$1\frac{5}{16}$" dia.
				9	$1\frac{5}{16}$" dia.	3600.	$1\frac{5}{16}$" dia.
						Ave. 3860.	
#2	1			11	$1\frac{5}{16}$" dia.	3110.	$1\frac{5}{16}$" dia.
				14	$1\frac{5}{16}$" dia.	2720.	$1\frac{5}{16}$" dia.
						Ave. 2915.	
#3	2			4	$1\frac{5}{16}$" dia.	2830.	$1\frac{5}{16}$" dia.
				4	$1\frac{5}{16}$" dia.	3140.	$1\frac{5}{16}$" dia.
						Ave. 2985.	
#4	4a			12	$1\frac{1}{4}$" dia.	2960.	$1\frac{1}{4}$" dia.
				7	$1\frac{1}{4}$" dia.	3280.	$1\frac{1}{4}$" dia.
						Ave. 3120.	
#5		77	.000010	2	$1\frac{1}{16}$" dia.	2470.	$1\frac{1}{16}$" dia.
	4b	78	.000034	6	$1\frac{1}{16}$" dia.	3710.	$1\frac{1}{16}$" dia.
						Ave. 3090.	
#8				9	$1\frac{1}{8}$" dia.	2240.	$1\frac{1}{8}$" dia.
	4c			6	$1\frac{1}{8}$" dia.	1910.	$1\frac{1}{8}$" dia.
						Ave. 2075.	
#9				14	$\frac{13}{16}$" dia.	4120.	$\frac{13}{16}$" dia.
	4d			14	$\frac{13}{16}$" dia.	3490.	$\frac{13}{16}$" dia.
						Ave. 3805.	

Note: All tests on diamond drill core of unknown orientation.

Hanover, New Mexico.

Horizon and Number	Ore Favorability	Permeability		Remarks	Impact Number	Crushing Strength Kg/cm²	Remarks
		Disc	Millidarcys				
Crinoidal (upper)	1	10	.0013	B			
		11	.0046				
		12	.0016				
		13	.00098				
		14	.00081				
		15	.00099				
		Ave.	.0013				
Crinoidal (lower)	2	8	.0002	B			
		9	.0002				
Lower Blue	3	1	.00003	B	1	682.	D
		2	.00005				
		3	.000003				
			.000028				

TABLE 9.—*Continued.*

Alma District, Colorado.

Horizon and Number	Ore Favorability	Permeability		Remarks	Impact Number	Remarks	Crushing Strength Kg/cm²	Remarks
		Disc	Millidarcys					
Leadville	1	D	.000015	B	5	B	1140.	B
					5	B		
Manitou	2	C	.000045	B	6	D	2320.	B
		59	.000059		8		3310.	
			Ave. .000052				Ave. 2820.	
Dyer	3	A	.000015	B				
		B	.000017					
			Ave. .000016					

Shafter, Texas.

Horizon and Number	Ore Favorability	Permeability		Impact Number	Crushing Strength Kg/cm²	Remarks
		Disc	Millidarcys			
#1	1	65	.0000012	1	1770.	
		66	.0000012	3	1870.	
		67	.000002	4	2320.	
			Ave. .0000015		Ave. 1990.	
#2	1	68	.000014	2	1980.	
		69	.0000045	2	2010.	
			Ave. .0000092		1370.	
					Ave. 1785.	
#3	2	72	.0000043	4	1680.	
		73	.0000037	5	1640.	
			Ave. .000004		2450.	
					Ave. 1920.	
#4	2	70	.000012	5	2380.	
		71	.00002	6	1640.	
			Ave. .000016	5	Ave. 2010.	
Penoles, "Sierra Mojada, Mexico"						
A	unfavorable	74	.000012			
A		75	.000032			
A		76	.000038			
			Ave. .000027			

Note: All of these tests were made on diamond drill core of unknown orientation.

TABLE 9.—*Continued.*

Gilman, Colorado.

Horizon and Number	Ore Favorability	Permeability		Remarks	Impact Number	Remarks	Crushing Strength Kg/cm²	Remarks
		Disc	Millidarcys					
#3	1	52	.00013	D	2	B	2410.	B
		53	.00016	D	3	S	1990.	B
		54	.00014	B	6	S	1250.	Cracked
		55	.000083	S	4	S	2530.	S
			Ave. .00013				2570.	S
							2910.	S
							Ave. 2480.	
#6	2	57	.0000021	B			1810.	B
		58	.0000023	B			1390.	S
		61	.0000019	S			Ave. 1600.	
			Ave. .0000021					
#8	3	62	.00000034	S	2	B	2140.	S
		63	.00000052	B	3	B	2640.	S
		64	.00048	D*	7	B	1780.	B
			Ave. .00000043				Ave. 2190.	

* Stylolite. Small crack?

and it is suggested that the most favorable horizon for replacement will be one which fails by mixed tension and shear, resulting in greater development of secondary permeability.

The test data suggest that within a given district the most favorable ore-bearing rock will not be the strongest or the weakest rock, but commonly the rock of intermediate character whose deformation pattern has been conditioned by its proximity to a stronger competent rock, or a weaker easily deformed rock. The implication is obvious that under these conditions the presumed favorable rock will have deformed in part by shear or tension under the influence of its proximity to the adjacent dominantly weaker or stronger rock. But as these qualities are only *relative,* the favorable rock will also show shearing or tension failure though less than the adjacent dominating rock, and relatively greater deformation of the other type not characteristic of the dominating rock.

More specifically, if three horizons, a strong sandstone, a dolomite, and a shaly limestone, are interbedded and subjected to common deformation, the shaly limestone will undergo greater shearing deformation than the sandstone, and the sandstone will have greater tension fracturing. The dolomite will participate in both of these deformations to an intermediate degree, resulting in intimate deformation of both types. There will be a development of fines and also of open porous texture, as shown in the crushing test specimens of intermediate fracture pattern. While the above example of sandstone-dolomite-shaly limestone is an extreme and ideal one, it is believed that careful laboratory tests as outlined will be helpful in identifying the fracture and deformation pattern of essentially similar rocks; which may be useful in the field interpretation.

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TABLE 9.—*Continued.*

Tri-State, Okla.

Horizon and Number	Ore Favorability	Permeability		Remarks	Impact Number	Remarks	Crushing Strength Kg/cm²	Remarks
		Disc	Millidarcys					
H	1	89	.000035	B	3	S	1090.	B
Fowler #3		90	.000036	S	3		1000.	B
							Ave. 1045.	
J	3	101	.0000063	B	3	B	1270.	S
Fowler #7					4	B		
K (upper half)	1	91	.000089	B*	3	S	1200.	B
		92	.000018	B*			1100.	B
Fowler #4		93	.000008	B			Ave. 1150.	
		94	.0000067	S				
		95	.0000095	S*				
		96	.0000088	S*				
			Ave. .000028					
M (middle)	1	97	.000031	B	4	B	1200.	B
Fowler #5		98	.000039	S	5	B	1730.	S
			Ave. .000035				Ave. 1465.	
M (middle-lower)	1	99	.0000036	B	4	B	1550.	B
Fowler #6		100	.0000017	S	4	B	1610.	S
			Ave. .0000027				Ave. 1580.	
M (lower-middle)	2	80	.000039	S	4	B	1360.	B
Fowler #1		81	.000032	B		B	1320.	B
			Ave. .000036				1060.	S
							Ave. 1245.	
M (lower)	2	82	.00011	S*				
Fowler #2		83	.00014	S	2	B	738.	S
		84	.00010	S	2	B	738.	S
		85	.00011	B*	2	B	809.	B
		86	.00011	B*			Ave. 760.	
		87	.00009					
		88	.00012					
			Ave. .00011					

Note: * With stylolite.

A further application of the above generalizations may be tentatively suggested as a probable explanation of the more widespread replacement of dolomite horizons than limestone horizons. While in the ultimate analysis the chemical difference between the two horizons no doubt plays a significant role in effecting the actual replacement, *the writer wants to stress the importance of making the horizons accessible to the ore-bearing fluids as a preliminary requisite to replacement.* Though no supporting experimental data are known to the writer, it is suggested that under the same confining pressure, *i.e.*, similar conditions of deformation, limestones tend to deform by "flowage" more readily than dolomites. In other words, higher confirming pressures are believed necessary to result in dolomite "flow," than limestone "flow." If this is true, *then under favorable conditions where limestones and dolomites*

are interbedded, the limestones may undergo considerable "flowage" (twinning, gliding, recrystallization), while the dolomites are undergoing fracturing and flow. No open spaces are developed during the "flowage" of the limestone so the "ground preparation" is inadequate, but the relatively permeable character of the fractured dolomite makes that horizon readily available to the ore-bearing fluids. See also the study by Hayward and Triplett (36), Hewett (35), and Currier (37).

The conventional toughness test, or measurement of impact strength, did not suggest any correlation to ore distribution. In general the tough rocks were also the strong rocks.

Tests on the relative grindability of the Tri-State and Bisbee limestones gave only random correlation to ore distribution. The strong rocks yielded less fines than the weak rocks. Further tests using more material and coarser crushing are suggested.

High impact number (*i.e.*, high toughness) and high crushing strength are generally associated in the test data. There is some suggestion of high crushing strength and low intergranular permeability association. The most permeable discs were in general from the coarsest-grained limestones.

In general, while these very limited initial tests were not productive of any usable guide to favorable horizons for ore, they have served to call attention to a type of investigation that has heretofore received little or no attention in mining geology research. The collection of representative samples appears to be the controlling factor limiting the value of the experiments. The next step in experimentation should be in the nature of a more detailed study based on a large number of specimens from a single mine. Crushing strength tests, and coarse crushing tests are believed to offer better chances for practicable application than either permeability or toughness tests. Measurement of some of the other usual physical constants, such as tensile and shear strengths, Poisson's ratio, etc., would be desirable to extend our knowledge of the physical characteristics of mineralized and un-mineralized ore horizons. There is no reason why the conclusions drawn, and suggested further studies, should not be extended to include also other types of mineralized rocks, rather than be limited only to limestone and dolomite.

ANNANDALE RD.,
FALLS CHURCH, VIRGINIA
Nov. 5, 1946.

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DISCUSSION AND COMMUNICATIONS

VIRGINIA TITANIUM DEPOSITS.

The paper by Davidson, Grout, and Schwartz in the November issue (vol. 41, pp. 738–748, 1946), "Notes on the ilmenite deposit at Piney River, Virginia," discusses a paper of mine on the "Occurrence and origin of the titanium deposits of Nelson and Amherst Counties, Virginia," published in 1941 as U. S. Geological Survey Professional Paper 198. The authors mentioned confined their study to a single deposit, and so my study of the district as a whole, extending over a period of several years, and comprising 38 pages and 19 plates with 55 figures, was not fully discussed. However, this wider study seems to have a bearing on the deposit at Piney River, and it is believed that these notes will clear up some points.

The discussion of origin is simplified by the statement by Davidson, Grout, and Schwartz (page 745) that "On the other hand we do not question his [Ross's] evidence that titanium minerals do replace some rock in the district"; and on page 746, ". . . some of Ross's specimens and pictures show a good deal of evidence that rutile and possibly ilmenite have at places been introduced along fractures into granulated 'anorthosite.'" Their conclusion is that the replacement origin does not apply to the Piney River deposit, and they say "90 per cent of the ilmenite [of this deposit] was of primary igneous dike formation." Thus the question of origin resolves itself into whether the two types of deposits, the disseminated ores and the nelsonites, had similar or different origins.

The study by these authors led them to conclude that the "Piney River titanium deposit was in large part intruded as an irregular dike [described as gabbro] fingering into its walls." Their Fig. 3 shows oriented, euhedral feldspar crystals, a somewhat different structure than I had observed in this deposit. I described ferromagnesian dikes elsewhere in the region and so their occurrence at Piney River would not be surprising. In fact the occurrence of such material would fit in very well with my observation that ilmenite is commonly associated with preexisting ferromagnesian rocks. However, I described and pictured rocks in the Piney River deposit that gave evidence of derivation from anorthosite rather than gabbro. These writers say, "Most of the ore in the pit is so much weathered as to yield only indefinite evidence of the original rock." I found it possible to obtain good thin-sections of any of this material. It was necessary to wrap the specimens in cotton till they could be impregnated with "kollolith," preparatory to grinding thin sections, and this procedure took care of even the most friable specimens. The thin-sections showed that weathering had only weakened the intergrain cement and the individual minerals and mineral relations were well preserved. A number of pictures of such thin-sections were reproduced in Plates 13–D, 14–C, and 15–A, B, C, and D, and indicate that these sections

carried an essential part of the story of nelsonite formation at Piney River. On the other hand, part of the material I studied from the "weathered" zone was much richer in pyroxenes and may have been the alteration product of a more ferromagnesian rock than typical anorthosite.

On page 743 these authors say, "This occurrence of ilmenite and apatite in fresh pyroxene in a fresh unsheared rock is to be contrasted with Ross's report that ilmenite is 'only with minerals that have invaded' pyroxene, chiefly hornblende, and 'nowhere occurs in the unaltered portions.'" Again on page 745 they say, "The rocks that are sheared show that ilmenite and apatite are sheared when the other minerals are, contrasting in this respect with the rocks Ross described. We find no rock at Piney River in which [quoting from Ross] 'ungranulated ilmenite and apatite are in thoroughly granulated rock.'" These three quotations, from my report, emphasizing granulations, were taken from sections discussing the relations in the disseminated ores and formed no part of the discussion of the nelsonites.

On page 746 they say, "Ross says, 'It is obvious that any explanation of nelsonite must apply to all types'; 'all minerals of the nelsonite have been formed by replacement of the anorthosite'; 'the titanium minerals . . . are confined to the granulated portions'; 'ilmenite is only with minerals that have invaded the clino-hypersthene crystals and nowhere occurs in unaltered portions'; evidently not the result 'of magmatic segregation.'" Here also the reference to titanium minerals in granulated rock was taken from sentences which were descriptions, not of nelsonite, but of disseminated ores within anorthosite; and were combined with two other parts applying to nelsonites. The reference to ilmenite invading clinohypersthene did not occur in a discussion of nelsonite, but was described and pictured in Plates 14–D and 17–A, B, and C of my paper as coming from the disseminated deposits of the American Rutile Company. I discussed the granulation of the anorthosite during its introduction as a mush of crystals, and so the same granulation could not extend to the post-intrusion nelsonites. That is, I could not have correlated granulation of anorthosite with shearing in nelsonite as implied by these authors, nor used granulation and sharing interchangeably in discussing the origin of the two types of deposits. These authors cite me as saying that it is "obvious" that all the nelsonite had the same origin, but in the following paragraph (page 747) they extend this to say, "From our work we must protest that it is not 'obvious' that one explanation for ilmenite formation must apply to all the ilmenite in the district." They seem to raise some objection to the statement that the same explanation should apply to all nelsonites. If there is objection to a single explanation of the nelsonites, what types are "magmatic" and what types have some other explanation?

They remark (page 746) that "This discovery [the origin of part of the titanium minerals by replacement], important as it was, seems to have led its discoverer [Ross] to ignore all other possible origins for ilmenite in the district." My whole paper revolved around the question as to whether an igneous or a replacement origin best explained their origin. Moreover they say on page 745, "Ross has not wholly ignored the possible origin of nelsonite as igneous dikes."

On page 747 there is the following: "Ross's claim that 'all the minerals' formed in a particular way implies that he saw all the deposits, which is unlikely . . ." and "It is rarely safe for any geologist to say what *did not happen*, unless his work is extraordinarily complete." My study was not confined to the Piney River occurrence but extended to all available exposures comprising a rather large group. However, new mining operation on two deposits (that on the Bryant farm, and that at Hanover near Richmond) made these deposits available for detailed study after publication of my paper. These deposits however, provided excellent confirmation of the earlier conclusions. I do believe that geologists, myself certainly included, should give careful consideration to all available deposits in a district before coming to important conclusions as to origin.

On page 747 the authors say, "In support of our claim that some ilmenite is of igneous crystallization we add that it has in the gabbro (Fig. 4) no such associated hydrous silicates as Shand has referred to as signs of hydrothermal attack (his stage 4), nor even the late magmatic silicates of his stage 3." But when they describe nelsonite ore, even lean ore, they repeatedly describe replacements and hydrothermal processes. On page 745 they say, "All the pyroxene is changed to amphibole (Fig. 8). . . . Fig. 10 shows that the effects of hot solutions are that apatite is corroded by the hydrous silicates; and Fig. 11 that pyrite is introduced replacing ilmenite," and on page 748, "It was later sheared and hydrothermally attacked. . . . The late hydrous magma probably caused deuteric changes, forming hydrous minerals; and hydrothermal attack carried the changes farther and replaced some of the ilmenite by pyrite."

The paper by Davidson, Grout, and Schwartz contains comments on my use of descriptive terms. Those particularly interested in these terms and their effectiveness in presenting the geologic picture will no doubt read the two papers. Therefore no comment is needed.

The stringing together of parts of sentences lifted from their context so that it appeared that these descriptions were of the nelsonites, when in fact they applied to those deposits in which a replacement origin is conceded, failed to give the reader the reasons for my conclusions. The basis for my conclusion about the origin of nelsonite was not that implied by the statement of these authors on page 745 where they say, "He considers two theories of origin of the ores and rejects the theory of introduction of ilmenite by igneous intrusion because its [quoting Ross, page 19] 'distribution seems to be in general controlled by shear zones.'" This quotation was from a section of my paper headed "Ferromagnesian Lenses" in which such lenses in the disseminated ores of the American Rutile Company, and not nelsonites, were being discussed. Also see Plates 6, 7 and 8 where these lenses are illustrated. Although these lenses were not part of the Piney River deposit described by Davidson, Grout, and Schwartz or of any other nelsonite body, they did show definite evidence that the ilmenite in them was a replacing material. The ilmenite in cleavage planes in pyroxenes proved its late introduction and the iron derived from these lenses had controlled the formation of ilmenite, while in the iron-free feldspar enclosing them only rutile formed. This

means that none of the interrelations shown by the district as a whole, and on which I did base my conclusions, were touched upon in the paper by Davidson, Grout, and Schwartz on the Piney River occurrence. In essence the problem of the origin of the titanium ores in the Virginia region was presented by showing that the disseminated ores could have formed only by replacement in a postmagmatic stage. This was followed by a detailed presentation of a wide variety of physical and mineralogical relationships which the two types of deposits had in common. The results of field observations supported by laboratory studies and interpreted in the light of physical chemistry were the basis for the conclusion that similar processes had produced both types of ores. This makes it seem advisable to restate the basis for these conclusions as briefly as possible. They are as follows:

1. The disseminated deposits, ilmenite and rutile, in anorthosite were formed by replacement (a granted relation).
2. This replacement was accompanied by later minerals totally absent in primary ungranulated feldspar, *i.e.*, amphiboles, micas, zoisite, quartz and apatite, and albitized feldspar.
3. A "horse" of typical anorthosite, many feet across, occurred in the Piney River nelsonite mass, and it contained the same group of minerals which characterized the anorthosite of the disseminated deposits including ilmenite, and graded into nelsonite.
4. The same type of feldspar as that characterizing the disseminated ores in anorthosite was abundantly scattered in augen-shaped masses through parts of the Piney River nelsonite.
5. Replacements were widespread in this body. Davidson, Grout, and Schwartz emphasize hornblende, but feldspar partly replaced by biotite (illustrated in the paper by Ross), abundant amphibole of the actinolite type, and chlorite were also present, all associated with ilmenite. The same minerals and mineral relations were characteristic of the disseminated deposits.
6. Besides the nelsonite, rich in ferromagnesian minerals, the Piney River body contained irregular local masses of nearly pure apatite-ilmenite (the hard ore). Identical apatite-ilmenite nelsonite, showing typical replacement relations and occurring in the disseminated ores in anorthosite where replacement is granted, was described and pictured by Ross. Similar relations were pictured from the Old General Electric Company mine where apatite and rutile occurred.
7. Ilmenite intruded hypersthene in the disseminated deposits and was pictured by Ross, but ilmenite is believed by Davidson and his associates to be magmatic and of the same age as hypersthene at Piney River.
8. The character of the containing rock exerted a very rigorous control of the character of the titanium minerals, rutile forming in nearly iron-free anorthosite, but ilmenite in rocks characterized by iron-bearing minerals. This relation was described by Ross from the American Rutile mines, but the same relation is beautifully shown in the more recently opened mines on the Bryant farm and at Hanover near Richmond. Here, very abundant veinlets are composed of rutile in feldspar, change to ilmenite on entering ferromagnesian mineral masses, and back to rutile on leaving these masses.
9. Ilmenite in many of the nelsonite bodies, that at Piney River included, has an extremely erratic and variable distribution, ranging from a few per cent up to apatite-ilmenite rock with 60 per cent or more of ilmenite.
10. Ilmenite fills veinlets in apatite in nelsonite from the Bob Hite farm, illustrated in Plate 14–A of my paper.
11. Numerous occurrences show replacement of rutile by ilmenite.
12. Nearly pure apatite-ilmenite ores occur locally at Piney River, and form numerous bodies elsewhere in the region.

The foregoing resumé of relationships would seem to make the following questions pertinent; questions which were not considered in the paper by Davidson, Grout, and Schwartz.

Replacement of the disseminated ores in the anorthosite is granted. A horse of anorthosite in nelsonite was replaced by minerals characteristic of nelsonite and graded over into typical nelsonite. Was this a minor local replacement or was it part of the general process?

Small masses of nelsonite formed in the disseminated deposits by replacement (see Plates 11 and 12 of my paper). Did typical apatite-ilmenite rock form from a magma in one place and by replacement in another occurrence in the same general area?

If material composed essentially of apatite plus 60 per cent or more of ilmenite formed from a melt, what was its temperature of fusion and what was its physical chemical origin? What would be the temperature of fusion of an apatite-rutile magma which gave 80 per cent of TiO_2?

If gabbro with minor proportions of ilmenite was the initial material of the Piney River nelsonite, how did it give rise even locally to a rock composed only of apatite and ilmenite? Some very real physical chemistry is involved here. What was it?

If the Piney River body formed from a melt, what is the explanation of the extremely erratic and variable distribution of ilmenite and apatite, a range of ilmenite from a few to at least 60 per cent?

If rutile and ilmenite formed by replacement in the disseminated deposits, why are the accessory minerals essentially the same in the nelsonite? The minerals of the two, anorthosite and nelsonite, differ greatly in relative proportions but not a single mineral has been observed in one deposit which is not duplicated in character and relationships in the other. Is a double origin, one replacement and the other magmatic, a reasonable explanation of the origin of two such closely related deposits in the same immediate region?

Ilmenite and quartz invaded clinohypersthene cleavage planes in the mine of the American Rutile Company (see Plate 17 of my paper), and hence is late, no matter whether the clinohypersthene is magmatic or hydrothermal. Again have clinohypersthene and ilmenite an entirely different origin in two closely related deposits?

Davidson, Grout, and Schwartz reject the mechanism for the origin of nelsonite proposed by me, but I can find in their paper no indication of a substitute mechanism for the formation of "igneous" nelsonite bodies from a normal gabbro with minor ilmenite and apatite.

This discussion is of necessity too brief to give a complete resumé of the relationships in the Nelson-Amherst Counties district, but persons with more than a casual interest in the origin of titanium minerals will presumably consult the U. S. Geological Survey Professional Paper 198, and in particular the 55 photographs illustrating relationships.

CLARENCE S. ROSS.

U. S. GEOLOGICAL SURVEY,
WASHINGTON, D. C.,
Feb. 5, 1947.

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REVIEWS*

Mineralogy and Geology of the Mesabi Range. By JOHN W. GRUNER. Pp. 127; plates 20; figs. 7. Iron Range Resources and Rehabilitation. St. Paul, Minnesota, in cooperation with the Minnesota Geological Survey.

This publication is a timely detailed summary of the mineralogy and geology of the Biwabik iron formation and ores of the Mesabi Range, Minnesota.

Much has been said recently about the inevitable exhaustion of the high grade iron ores of the Mesabi range which, during the war period, were mined and shipped to the war hungry blast furnaces at an astounding rate. This wartime peak production of ore has directed attention to the parent iron formation as a probable future source of iron ore and to the research on processes of concentrating this iron formation or "taconite" now being diligently investigated.

A special chapter deals with the magnetite deposits which are especially important from a concentrating viewpoint. The author estimates the presence of about 5 billion long tons of magnetic taconite within 230 feet of surface (disregarding glacial drift), which could yield about 1.7 billion long tons of magnetic concentrates (assuming all this material could be quarried). Large sections of oxidized taconite are properly omitted from this estimate and considered in a separate chapter.

The mineralogy of the taconite is reviewed with emphasis on the silicates minnesotaite, stilpnomelane and greenalite, and the carbonate siderite, which are the primary source of most of the oxide ore minerals.

The petrography, subdivisions and structure of the iron formation and a revised average analysis of it are also presented.

The origin of the iron formation and the ores is reserved for a later monograph, thereby restricting the text to factual data with a minimum of theory. Illustrations are excellent.

This book is highly recommended to those interested in any phase of the pre-Cambrian iron formations of the Lake Superior District.

R. H. B. JONES.

Oil for Victory, the Story of Petroleum in War and Peace. By the Editors of Look. Pp. 287; illustrated. McGraw-Hill Book Co., New York, 1946. Price, $3.50.

This book covers more than is stated in its title for it is essentially a story of people obtaining, piping, refining, shipping and using petroleum in war. Its twelve chapters deal with the important part played by oil in the war; Mobilizing an Industry; Peril on the Sea; Oil Underground, on Water and on Land; Test Tube to Toyko; Alchemy Wholesale; Searchers in Far Places; Tundra, Sea and Jungle; and Oil for a World at Peace. It is mainly a story in pictures; they exceed the text. It is an interesting book for the non-technical reader.

* Books noted under *Reviews* and *Books Received* may be ordered through the Economic Geology Bookshop, M. M. Leighton, Urbana, Ill., but orders for official reports and single copies of Journals should be sent directly to their publishers.

Mines Register, successor to the **Mines Handbook**—1946 Edition.

For over 40 years the Mines Register and its predecessors have been the standard reference on mining companies and mining properties for engineers, libraries, banks, financial houses, and mining companies and supplies. It refers to 22,000 active or dormant mines of the world.

This 22nd edition is the last one since 1942 and naturally the changes in the price of metals, premium prices for metals, subsidies, new metal prices, discoveries and reopening of old mines, and changes in ownership have brought a host of revisions that appear in this volume. It is, therefore, much larger than the last volume. The same procedure is followed in this volume. First are comprehensive treatments of the active mines in the Western Hemisphere, followed by active mines in other parts of the world. Then follow sections on geographic directory of mines, dormant mines, mining company officials, Engineers, and metal industry statistics.

BOOKS RECEIVED.

ALAN T. BRODERICK.

The Iron Ore Bearing Formations of Ohio. W. STOUT. Pp. 230; tbls. 3. Geological Survey of Ohio, 4th. ser. Bull. 45. Columbus, 1944. *Orderly compilation of available data on ores. Last mined in 1916, still have future.*

Perlite Deposits Near the Deschutes River, Southern Wasco County, Oregon. J. E. ALLEN. Pp. 17; pls. 8. Oregon Department of Geology and Mineral Industries. Short Paper No. 16. Portland, 1946. *Geology of district and of producing mine. Metallurgy, laboratory tests, analyses.*

Lineation. E. CLOOS. Pp. 122; pls. 10; figs. 15. Geological Society of America, Memoir 18. Geological Society of America House, New York City, 1946. *Thorough treatise based on author's work and exhaustive search of English, French, German, Scandinavian literature. 6 causes of some 15 kinds of lineation discussed. Confusion due to frequent misunderstanding of terminology and excessive simplification and generalization pointed out. More careful observation and recording of data recommended. Well illustrated, contains lineation map of E. Maryland and S. E. Penn. Annotated Bibliography (1825–1945).*

Comunicacões dos Serviços Geológicos de Portugal. Serv. Geol. de Port. Tomos 24 & 25. Lisbon, 1943.

Tômo 24: pp. 155; pls. 50; tbls. 2; maps 5. *10 papers on areal geology, pliocene paleontology, paleobotany, hercynian granite petrology, archeology, interglacial elephant remains, Ponsul fault geomorphology.*

Tômo 25: **"Jazigos Portugueses de Cassiterite e de Volframite."** J. M. COTELO NEIVA. Pp. 253; figs. 97; pls. 45. *Report on Portuguese cassiterite and wolframite deposits. English summary.*

O estudo da jazida de wolframita de Inhandjara (Brazil). R. SALDANHA. Pp. 100; figs. 32; microphotos 5. Universidade de São Paulo, Bull. 60, Mineralogia No. 8. S. Paulo, 1946. *Geological and mineralogical description of the tin and tungsten veins of São Paulo State, Brazil. English summary.*

Kenogami Lake Area, Timiskaming, Ontario, Geological Map. Ontario Dept. of Mines Map No. 1946–1. Toronto, 1946. *16 × 31", 1:12,000, colored.*

The Occurrence of Flint in Ohio. W. STOUT, R. A. SCHOENLAUB. Pp. 110; pls. 11. Geol. Surv. Ohio, 4th. Ser., Bull. 46. Columbus, 1945. *Lithology and stratigraphy of Silurian to Pennsylvanian flint-bearing marine limestone and dolomite. Analyses, petrography, photomicrographs.*

Records of Boreholes 21 to 40, Waterberg Coalfield, Union of S. Africa. Pp. 132; pls. 2. U. of S. Africa Dept. Mines, Geol. Series, Bull. 16. Pretoria, 1946. *Core logs, coal analyses of coal field in Ecca Series rocks.*

The Physical Features of Carroll County and Frederick County (Maryland). Pp. 312; figs. 31; pls. 23. Maryland Dept. Geol., Mines, Water Res. Baltimore, 1946. *Geography, Geology and water resources, soils, forests, climate, magnetic declination.*

Cretaceous Stratigraphy of the Belvidere Area, Kiowa County, Kansas. B. F. LATTA. Pp. 43; pls. 3; figs. 3. Kansas Geol. Surv., Bull. 64, Part 6. Lawrence, 1946. *Type area for Comanchean series of Early Cretaceous in Kansas.*

Congo Belge et Ruanda-Urundi Bulletin du Service Géologique. Pp. 184; tbls. 7; maps 3; photos 4; figs. 21. Serv. Geol. Reg. de Léopoldville, Bull. No. 1. Léopoldville, 1945. *Geology and stratigraphy of the Kalahari, Karroo and E. Congo systems of the Lindi group and the pre-lower Congo tillite formations. Bedrock-soil correlation.*

Ground-Water Conditions in Arkansas River Valley in the Vicinity of Hutchinson, Kansas. C. C. WILLIAMS. Pp. 71; pls. 6; figs. 11; tbls. 4. Kansas Geol. Surv. Bull. 64, Part 5. Lawrence, 1946.

Petroleum Development and Technology. Pp. 292; figs. 163; tbls. 17. Amer. Inst. Min. and Met. Eng. Trans. Vol. 165. New York, 1946. *21 papers. 10 research, 10 production engineering, 1 review 1945 refining.*

New Mexico Bureau of Mines and Resources Annual Report, July 1, 1945–June 30, 1946. E. C. ANDERSON. Pp. 42. Socorro, 1946.

State Department of Geology and Mineral Industries of Oregon, Fifth Biennial Report. July 1, 1944–July 1, 1946. Pp. 38; ills. 4. Oregon Dept. Geol. and Min. Inds. Bull. 32. Portland, 1946.

Uganda Geological Survey Annual Reports, 1940, 1941. Pp. 64; tbls. 4. *Reports on field and headquarters work.*

Geologic Map of North America, compiled by GEORGE W. STOSE. Scale 1:5,000,000. Geol. Soc. of America, 1946. *Cooperation of Federal, State and Provincial Geological Surveys of United States, Canada and Mexico; in colors and in more detail than its predecessor.*

Alaska Map E. Scale, 1:2,500,000. U. S. Geol. Survey, Washington, D. C., 1946. *No topography; shows natural features.*

Geologic Map of Illinois, compiled by J. MARVIN WELLER AND OTHERS. Scale, 1:500,000. Ill. State Geol. Survey, Urbana, 1945. *Colors; cross-sections; stratigraphic columns.*

Geologic Map and Structure Sections of Mascot—Jefferson City Zinc Mining District, Tennessee. JOSIAH BRIDGE. Scale, 2 in = 1 mile. 40 × 60″. Tenn. Div. of Geology, 1945. *Topography, Geology in colors, cross-sections.*

Glacial Map of North America, Committee of Division of Geology and Geography, Natural Research Council, RICHARD F. FLINT, Chairman. Scale, 1:4,555,000. Geol. Soc. of America. New York, 1945. *Topography; areal colors and symbols denoting existing glaciers; marine submergence; extinct glacial lakes; outwash; various drifts; strial; direction of flow; and various glacial features.*

Oil and Gas Investigations Prel. Map No. 61. Part of New Mexico. Scale, 1 in = 10 miles. U. S. Geol. Surv. in cooperation with New Mexico State Bureau of mines and mineral Resources, Washington, D. C., 1946. *Geologic map and stratigraphic sections of palcozoic rocks of part of New Mexico; footnotes.*

Geologic Map of Messina and Surrounding Country. Scale, 1:50,000. Geol. Surv. of S. Africa. Pretoria, 1944 (1947). *Colored map and structure sections of complicated area of gneisses, basic igneous rocks, sediments and quartz veins of copper region.*

SCIENTIFIC NOTES AND NEWS

ELIOT BLACKWELDER, emeritus professor of geology at Stanford University, has been elected as an honorary foreign member of the Geological Society of London.

OLAF P. JENKINS has been appointed Chief, Division of Mines, Department of Natural Resources, California, effective February 1, 1947. Mr. Jenkins has been with the Division of Mines since 1929, as Chief Geologist, and previously he was associated with the state departments in Washington, Arizona and Tennessee, and served as consultant for several mining companies. He spent 3 years with the Standard Oil Company of New Jersey in the Dutch East Indies, and 7 years as professor of economic geology at the State College of Washington.

J. B. TYRRELL, 88 years old, has been awarded the Wollaston Medal by the Geological Society of London.

IRA B. JORALEMON, consulting geologist, recently returned to his office at 315 Montgomery St., San Francisco, from a professional trip to Venezuela.

JOHN ZIMMERMAN, JR., has been appointed chief geologist for the Permanente Cement Co., with headquarters at the main plant of the company, at Permanente, Santa Clara County, Calif.

HOBART E. STOCKING, of the Department of Geology, Oklahoma A. and M. College, has been awarded the honor of "Professor Honorario" by the Faculty of Sciences, University of Costa Rica, where he served as visiting professor during 1945.

RALPH W. MARSDEN is associate professor of geology at the University of Oklahoma, Norman.

PATRICK M. HURLEY has joined the staff at Massachusetts Institute of Technology as assistant professor of economic geology.

CHARLES CAMSELL, deputy minister of the Department of Mines and Resources, Ottawa, has been elected an Honorary Member of the Canadian Institute of Mining and Metallurgy.

WILSON D. MICHELL, chief geologist for the Magma Copper Co., Superior, Ariz., for the last two years, left in January for Morocco, North Africa, where he will be engaged in mine examination work for the next year or two.

J. K. GUSTAFSON, geologist for the Newmont Mining Corp., sailed for Australia the latter part of January on a six months' leave of absence to do consulting work for the Zinc Corp., Broken Hill, New South Wales, and associated companies.

H. W. STRALEY, 3RD, has taken an assistant professorship in geology at the Georgia School of Geology in Atlanta.

EARL K. NIXON joined the staff of the Kansas Geological Survey at the University of Kansas as oil and gas geologist early in January.

The Branner Geological Society of Southern California held its annual meeting at the California Institute of Technology on March 5. The principal address was delivered by Dr. K. O. Emery of the University of Southern California on "The Submarine Geology of Bikini Atoll."

Officers for the ensuing year were elected: Vernon L. King (Consulting Petroleum Geologist and a former student of the late John Casper Branner), President; Richard H. Jahns (California Institute of Technology), Vice-President; and William H. Easton (University of Southern California), Secretary-Treasurer. Retiring officers are: William C. Putnam (University of California at Los Angeles), President; William Winham (Standard Oil Company of California), Vice-President; and Richard Ten Eyck (Continental Oil Company), Secretary-Treasurer.

Emmons Memorial Fellowship

The S. F. Emmons Memorial Fellowship in Economic Geology is available for this year, with a stipend of $1,500.00. Applications and accompanying testimonials should be submitted not later than May 15, 1947. Applicants should be qualified by training and experience to investigate some problem in Economic Geology and should submit a definite statement of the problem to the Committee, under whose oversight the work may be undertaken at any institution approved by them. The Fellow must give entire time to the problem, which may be used for a doctorate dissertation. Application blanks may be obtained from Alan M. Bateman, Yale University, L. C. Graton, Harvard University, Paul F. Kerr, Columbia University, or the Secretary, Columbia University.

The Fellowship will be awarded again for the academic year 1948–49, announcement of which will be made late in 1947.

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